

**Science in the Twentieth
Century:
A Social-Intellectual Survey
Part I
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Steven Goldman has degrees in physics (B.Sc., Polytechnic University of New York) and philosophy (M.A., Ph.D., Boston University) and, since 1977, has been the Andrew W. Mellon Distinguished Professor in the Humanities at Lehigh University. He has a joint appointment in the departments of philosophy and history because his teaching and research focus on the history, philosophy, and social relations of modern science and technology. Professor Goldman came to Lehigh from the philosophy department at the State College campus of Pennsylvania State University, where he was a co-founder of one of the first U.S. academic programs in science, technology, and society (STS) studies. For 11 years (1977–1988), he served as director of Lehigh's STS program and was a co-founder of the National Association of Science, Technology and Society Studies. Professor Goldman has received the Lindback Distinguished Teaching Award from Lehigh University and a Book-of-the-Year Award for a book he co-authored (another book was a finalist and translated into 10 languages). He has been a national lecturer for Sigma Xi—the scientific research society—and a national program consultant for the National Endowment for the Humanities. He has served as a board member or as editor/advisory editor for a number of professional organizations and journals and was a co-founder of Lehigh University Press and, for many years, co-editor of its Research in Technology Studies series.

Since the early 1960s, Professor Goldman has studied the historical development of the conceptual framework of modern science in relation to its Western cultural context, tracing its emergence from medieval and Renaissance approaches to the study of nature through its transformation in the 20th century. He has published numerous scholarly articles on his social-historical approach to medieval and Renaissance nature philosophy and to modern science from the 17th to the 20th centuries and has lectured on these subjects at conferences and universities across the United States, in Europe, and in Asia. In the late 1970s, the professor began a similar social-historical study of technology and technological innovation since the Industrial Revolution. In the 1980s, he published a series of articles on innovation as a socially driven process and on the role played in that process by the knowledge created by scientists and engineers. These articles led to participation in science and technology policy initiatives of the federal government, which in turn, led to extensive research and numerous article and book publications through the 1990s on emerging synergies that were transforming relationships among knowledge, innovation, and global commerce.

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Science in the Twentieth Century: A Social-Intellectual Survey

Scope:

In the course of the 20th century, the practice of science, professionally, intellectually, and in relation to society, increased in scope, scale, and complexity far beyond what had been anticipated at the end of the 19th century. All of the sciences became inextricably entangled with social, political, and commercial forces and values. From the perspective of society, at least, this erased the distinction between pure and applied science, between knowledge and its “fruits,” which had been passionately espoused by many leading 19th-century scientists. As scientists created increasingly powerful theories, people—often scientists themselves—applied those theories to develop technologies whose exploitation created new wealth, new forms of power and control, new ways of life...and new dependencies on more science to create newer technologies!

Concurrently, the practice of science became increasingly formalized, institutionalized, and professionalized. This professionalization reflected and was driven both by the rise of a large number of people who made a living as scientists, in comparison with the comparatively modest community of mostly gentlemen scientists in the 19th century, and by the steadily increasing significance of science to society from the last third of the 19th century through the 20th century. Two hundred and fifty years after the pioneering work of Descartes, Francis Bacon, and Galileo, science suddenly mattered—not just to intellectuals, but to everyone and in profoundly existential ways.

Intellectually, too, the discoveries and theories of 20th-century physical, life, and social scientists exceeded anything that had been anticipated, even by the greatest of 19th-century scientists. As 1900 approached, leading physicists claimed that, apart from the details, the task of science was nearing completion; however, by the end of the 20th century, effectively every 19th-century theory of natural and social phenomena would be overthrown or superseded.

The first lecture in this course establishes its objective: to trace an intellectual history of the physical, life, and social sciences in the 20th century, organized around an evolving scientific understanding of matter and energy, the universe, Earth, life, and humanity, subsuming under the last category theories of culture, society, and mind.

Complementing this survey of a century of science from the “inside,” in terms of its ideas and discoveries, will be an account of the evolution of 20th-century science from the “outside,” that is, of its evolving relationship with society. It is this reciprocal relationship between science and society that makes an understanding of the sciences as a whole in the 20th century important, and not

simply as history, because science is implicated in all of our 21st-century prospects, the threats no less than the promises.

Lectures Two through Eleven describe our evolving understanding of matter and energy, the foundations of the physical and life sciences. We begin with the special and general theories of relativity and how they redefined what we mean by space, time, matter, energy, and motion: in short, what the framework of reality is for the physical sciences.

Given that quantum theory is the most important and intellectually revolutionary scientific theory of the 20th century, eight lectures are devoted to it. Lectures Three and Four trace the early history of the theory, from the tentative introduction of the quantum hypothesis in 1900 to the formulation of quantum mechanics in 1925 and its radical Copenhagen interpretation in 1929. Our goal is a qualitative appreciation of the innovative ideas underlying the theory and of the bizarre microworld underlying ordinary experience that it revealed. Lectures Five through Eight describe the creation and application of the second stage of quantum theory's development, quantum electrodynamics (QED), from 1929 to 1965. Lectures Nine and Ten describe the transition from QED to quantum chromodynamics (QCD) and the unification of all known fundamental forces of nature.

Lecture Eleven concludes the discussion of matter and energy by highlighting major events in the evolution of chemistry, emphasizing the transformation wrought by its assimilation of quantum theory and its growing power to create molecules by design.

The obscurity of the theories of 20th-century physical science from the perspective of the non-scientist public is overwhelmingly a consequence of the forbidding mathematics that has become the language of science. Lectures Twelve and Thirteen discuss controversies in the first half of the 20th century over the relationship between mathematics and truth, and between mathematics and reality, as well as the astonishing fertility of abstract mathematics for the sciences, even if the source of that fertility is not understood.

What we mean by the *universe* has changed, from 1900 to 2000, far more dramatically than anything else in the history of science, more even than the change wrought by Copernicus. Today, the universe is unimaginably more vast than it was thought to be in 1900, and the stories of its origin, constitution, and fate, discussed in Lectures Fourteen through Sixteen, are beyond science fiction!

Lectures Seventeen through Nineteen focus on our knowledge of planet Earth, especially the shift from a geology of static continents to plate tectonic theory. We also discuss the growing recognition of the Earth as a complex system, integrating a dynamic, evolving, physical Earth with its biosphere, oceans, atmosphere, and external and internal magnetic fields, the whole interacting with the solar system in general and the Sun in particular.

Lectures Twenty and Twenty-One address the “outside” of science, especially the rise of techno-science (science-based technology) and its connections to government, industry, and society.

Lectures Twenty-Two through Twenty-Six address our understanding of life, treating the history of evolutionary biology, human evolution, genetics, molecular biology, and science-based medicine.

Lectures Twenty-Seven through Thirty-Four focus on our knowledge of humanity. This group includes three lectures on the evolution of anthropological theories of human culture, the field and theoretical work of archaeologists, important developments in linguistic theory, and changing conceptions of history as a science. Three lectures describe theories of society, the state, and economies, theories that have had profound implications for national and global political agendas and actions in the course of the 20th century. Two lectures describe changing theories of the human mind, our most intimate attempt at self-understanding, from the enormously influential theories of the unconscious by Freud and Jung early in the century, through the equally influential behavioral psychology that dominated the mid-century, to the cognitive psychology that came to the fore in the late century, especially cognitive neuroscience allied to artificial intelligence research.

Lectures Thirty-Five and Thirty-Six review the major concepts of 20th-century science and discuss their broader cultural and intellectual significance, survey the leading edges of the sciences at the close of the 20th century, and look ahead to the continuing evolution of science in the 21st century.

Lecture One

The Evolution of 20th-Century Science

Scope: Twentieth-century science is an *evolutionary* outgrowth of 19th-century science: intellectually, in terms of the theories scientists created and the new ideas underlying them; in its organization and conduct as a professional practice; and in its relationship to society. As powerful and innovative as 19th-century science was by comparison with 17th- and 18th-century science, it is dwarfed by the scale, scope, and power of 20th-century science. Our goal is a rounded appreciation of what science became in the course of the 20th century: a cultural force in virtue of its reality-defining worldview and a force driving social change through its relation to industry and government.

From its 17th-century birth, modern science has had two mutually influential “sides”: an “inside,” intellectual dimension, and an “outside,” social relationship dimension. The inside, the outside, and the relationship between them all changed character in the course of the 20th century. Our exploration of the inside of science will be organized around the evolving 20th-century understanding of Matter and Energy, the Universe, Earth, Life, and Humanity. The outside will be organized around the relationship of science to society-transforming technological innovation, to government, and to public institutions and values.

As 20th-century physical, life, and social science are built on 19th-century science, identifying developments in 19th-century science that played key roles in 20th-century science is a precondition for appreciating the innovativeness of 20th-century science. A preview of the major theories and the core ideas that cut across the scientific disciplines will help orient us as we begin tracing the rise of these innovative theories and ideas.

Outline

- I. This course will take us on an intellectual odyssey, as we explore the evolution of the sciences and of the relationship between science and society in the course of the 20th century.
 - A. Our study will span the physical, life, and social sciences without distinguishing between the “hard” sciences of, for example, physics and chemistry, and the “soft” sciences, such as economics and sociology.
 - B. We apply the term *evolution* to our study of 20th-century science in the sense that it was used by Charles Darwin and Alfred Russell Wallace;

that is, *evolution* is the emergence of novelty by the introduction of discontinuity into an underlying continuity.

- C. Our exploration will be organized around five broad themes: Matter and Energy, the Universe, the Earth, Life, and Humanity. We will also look at several seminal developments in mathematics that profoundly influenced the practice and application of science in the 20th century.
 - D. Our survey, then, has a dual structure. We will look at the intellectual “inside,” that is, the ideas and theories of 20th-century science, as well as its “outside,” seen in its relationship to society.
- II. We begin by identifying the core ideas of 19th-century science that underlie the evolution of 20th-century science.
- A. In the 19th century, the *atom* came to represent the view that natural phenomena consisted of fundamental building blocks that could be configured to produce the vast number of forms we find in nature. The atom in physics and chemistry is an example of that conception, as are the gene in the theory of heredity and the germ in the germ theory of disease.
 - B. In the 19th century, a science of *energy* was created, called *thermodynamics*, which identified energy as a new dimension of reality. This science recognized that energy was a phenomenon in nature parallel to matter.
 - C. The 19th century also saw the development of the idea of *fields* of energy and force. A field is an immaterial phenomenon obeying natural laws and capable of exercising forces on material objects.
 - D. Chemists in the 19th century discovered that *structure* is the feature that differentiates one substance from another, as opposed to the fundamental constituents of substances and the properties of these constituents.
 - E. The fifth core idea of the 19th century that would influence 20th-century science was the discovery of *non-Euclidean geometry*. For approximately 2,300 years before the mid-19th century, Western philosophy, science, and mathematics were based on the confident assumption that deductive reasoning was closely linked to truth. In the mid-19th century, mathematicians discovered deductively perfect geometries that contradict Euclidean geometry, raising the question of which form of geometry is true of space and severing the uncritical connection between reasoning and reality.
 - 1. Another important development in mathematics in the 19th century was the invention of symbolic logic. From this development, we learned that notation can have a significant impact on our thinking. Simply replacing words with symbols can lead to new insights.
 - 2. Further, symbolic logic undermined the notion that subjects had priority over predicates, that is, that things were the ultimate reality

and relationships were a secondary consequence of the organization of things. Through the use of symbolism, relationships were found to have properties of their own.

- F. The 19th century also saw the replacement of Newton's particle, or corpuscular, theory of light with the *wave theory of light* and the subsequent expansion of this theory with James Clerk Maxwell's *electromagnetic theory of energy*.
 - G. *Probability* and *statistics* became important in the 19th century, specifically, the idea that natural processes exist that require probability to describe them.
 - H. Finally, the 19th-century theory of *evolution* was a foundational idea of 20th-century science.
- III. We also need to mention three of the many instruments that were invented in the 19th century that will reappear throughout the course.
- A. The first of these is the *color-corrected microscope*, which enabled high-power magnification without blurring.
 - B. Another important scientific device of the 19th century was the *spectrometer*, which identifies the frequencies of a beam of light.
 - C. Finally, the invention of the *interferometer* allowed scientists to measure extremely small distances and would be integral to the development of 20th-century astrophysics.
- IV. What features of the 19th-century social context were critical in the evolution of 20th-century science?
- A. In the 19th century, technological innovation emerged as the primary agent of social change, displacing the dominance of religion and politics.
 - B. This development was reinforced by the invention of the industrial research laboratory, the emergence of the university as a center for scientific research, and governments' use of scientific research in pursuit of military, economic, and social policies.
- V. Certain ideas that cut across disciplines emerged as distinctive features of 20th-century science.
- A. The first of these is the idea that reality is ultimately describable in terms of *relationships*.
 - B. Connected to the first idea are the concept of *systems* and analysis of natural phenomena from the top down, rather than a building up of reality from elementary parts.
 - C. Another important idea of the 20th century is *dynamism*; that is, the notion that change is a normal state.

- D. Also, *information* is understood as a feature, or category, of reality, similar to matter or energy.
- E. The 20th century also finds that unlimited complexity can emerge out of simplicity.
- F. Over the course of the century, the distinction between subjectivity and objectivity, between mind and world, becomes blurred.
- G. Finally, in the 20th century, scientific research becomes increasingly cross-disciplinary and collaborative.

Essential Reading:

William Coleman, *Biology in the Nineteenth Century: Problems of Form, Function, and Transformation*.

P. M. Harman, *Energy, Force and Matter: The Conceptual Development of Nineteenth-Century Physics*.

Mary Jo Nye, *Before Big Science: The Pursuit of Modern Chemistry and Physics, 1800–1940*.

Questions to Consider:

1. Why did Western societies become so much more receptive to science in the 20th century?
2. How is it that a public so uneducated in science can be so influenced by scientific theories and ideas?
3. Granted that the conduct of science is influenced by the social context in which it is practiced, can that context also influence the content of science, and how does it do that?

Lecture Two

Redefining Reality

Scope: The special theory of relativity (STR) undermined 200 years of physics. How did Einstein come to formulate STR, the subject of just one of three papers he published in 1905 that moved physics in new directions? What problem was Einstein trying to solve and how did his solution entail nothing less than a reinterpretation of space, time, motion, causality, energy, and matter: thus, a reinterpretation of physical reality? Why is it called the “special” theory of relativity and what is relative about it? As late as 1921, when Einstein was awarded the Nobel Prize in physics, relativity theory was still suspect in conservative scientific circles, and he was awarded the prize for another 1905 paper: a pioneering contribution to quantum theory. STR was, for a time, not susceptible of empirical validation, but beginning in the late 1920s, its validity became inescapable and its utilization necessary for both theoreticians and experimentalists.

In the general theory of relativity (GTR), Einstein extended STR into a new, anti-Newtonian, universal theory of gravity in which space, time and motion, matter, energy and force became types of relationships and not the absolute entities they were in Newtonian science. At the same time, GTR entailed a wholly unexpected revision in our conception of the universe, as unlimitedly large but finite and, incredibly, expanding, implying temporal finitude as well. Especially after 1960, experimental testing of GTR became possible and astronomical observations have confirmed long-ignored predictions of the theory, including the existence of neutron stars, galactic lenses, and black holes.

Outline

- I. In 1905, Einstein published three papers, each one influential in changing the history of 20th-century science.
 - A. The first of these was a paper on *Brownian motion*. In this phenomenon, small particles suspended in fluid are observed to move around at random. In the course of explaining Brownian motion, Einstein convinced many of his fellow physicists of the existence of atoms.
 - B. The second paper, which we will discuss in the next lecture, was on the *photoelectric effect*. Einstein explains the phenomenon that certain materials, typically metals, when exposed to light, give off electrons. Einstein won the Nobel Prize for this paper, which is one of the foundations of quantum theory.
 - C. Of course, Einstein’s third paper was on the *special theory of relativity*.

- II.** What were the problems that Einstein's special theory of relativity was trying to solve?
- A.** The first problem was one that the physics community shared: Using the wave theory of light, physicists tried to measure the motion of the Earth in absolute space, but every attempt resulted in a measurement of 0. Further, every measurement of the speed of light in a vacuum resulted in a constant, a result exhibited by no other form of motion in nature.
 - B.** The second problem was a seemingly simple one that troubled Einstein personally: What does it mean to say that two events, one at a distance from an observer and one close to the observer, occur simultaneously? In fact, the event that occurs at a distance must take place earlier, because it takes time for the light signal from that event to reach the observer.
 - C.** Einstein solved both problems in the special theory of relativity, which rests on two principles.
 - 1.** The first principle is one that had been accepted by physicists for 300 years, that is, the principle of the relativity of motion. For two observers who are traveling at a uniform speed and subject to uniform forces, the laws of physics identified by both will be the same.
 - 2.** The second principle was to accept as an axiom that the speed of light in a vacuum is a constant for all observers, regardless of their motion.
 - 3.** What follows from taking these two principles together is the special theory of relativity, which includes a new view of space and time as relationships, not things.
 - D.** Until 1905, space and time were accepted by scientists as Newton had defined them.
 - 1.** Space had a Euclidean character that existed independently of anything in space; in other words, space was an absolute, infinite, and uniform container for matter. Time was an absolute, uniform "clock" ticking in the background at a constant rate.
 - 2.** According to the special theory of relativity, all spatial and temporal measurements are, instead, relative to an observer's frame of reference; space and time are not absolute and uniform.
 - E.** The special theory of relativity required rethinking our definitions of space and time, but perhaps more dramatically, it resulted in the equation $E = mc^2$. Matter and energy, which were considered to be two distinct categories of nature throughout the 19th century, were, in fact, interconvertible.

- III.** Between 1905–1917, Einstein was working to further develop his contributions to quantum theory and to generalize the special theory of relativity.
- A.** In the wake of the special theory of relativity, Einstein was concerned with a peculiar feature of Newtonian science that had been unquestioned until the early 20th century. This feature of physics is that *gravitational mass* (weight) and *inertial mass* (the resistance of matter to motion) are identical. Einstein wondered why this is true.
 - B.** Again, Einstein proposed to make this equivalence a new principle of nature. What emerged was a new universal theory of gravity, in which space, time, matter, and energy are intimately related.
 - 1.** *Space* and *time* are now names of relationships, and so is *matter*. The mass of an object is, in some way, dependent on the total distribution of mass in the universe.
 - 2.** When a star explodes and its mass is dispersed in space, that event has implications for the shape of space throughout the universe.
 - 3.** Space and time, then, are relationships. They have no reality apart from their connections with matter and energy.
 - 4.** Further, space has a shape; it is not featureless in all directions. The shape of space is a function of the distribution of matter and energy in space.
 - 5.** Finally, space is not infinite.
 - C.** The first experimental confirmation of this general theory of relativity came in 1919, when Sir Arthur Eddington observed that light rays passing close to the Sun during an eclipse were “bent” almost exactly as predicted by the theory.
- IV.** The general theory of relativity has dramatic consequences that are still being played out.
- A.** The general theory of relativity is explicitly *ontological*; that is, it describes reality. The special theory of relativity can be interpreted *metrologically*, that is, as a statement about what we can measure.
 - B.** The general theory of relativity predicts gravity waves, which have not yet been detected. According to the theory, a change in the distribution of matter in the universe should cause waves to ripple through space and affect the shape of space; we should be able to detect these waves.
 - 1.** At the end of the 20th century, NASA funded America’s first gravity wave telescope, which is based on the interferometer invented in the 19th century.
 - 2.** This device is several miles long and is capable of detecting a change in the distance between two fixed points as small as the diameter of a proton.

- C. The most amazing prediction of the general theory of relativity is that the universe is expanding at an accelerating rate, which Einstein himself initially did not believe could be correct.
- D. We will return to the cosmological implications of the general theory of relativity in a later lecture; in the next lecture, we'll turn to quantum theory and the attempts to unify it with the general theory of relativity.

Essential Reading:

Albert Einstein, *Relativity: The Special and General Theories*.

Abraham Pais, *Einstein Lived Here: Essays for the Layman*.

John Stachel, *Einstein's Miraculous Year*.

Supplementary Reading:

Ronald Clark, *Einstein: The Life and Times*.

Questions to Consider:

1. How is it that theories like STR and GTR that are based on rethinking existing ideas can reveal absolutely unthought-of aspects of reality?
2. If matter and energy are interconvertible, as Einstein's equation correctly predicted, then what is the reality of which they are complementary expressions, or is this not a legitimate question?
3. Intuitively, we grasp calling "things" real, but how can relationships be what reality ultimately is made of?

Lecture Three

Quantum Theory Makes Its Appearance

Scope: The special and general theories of relativity were the unanticipated offspring of what the eminent British scientist Lord Kelvin called one of “two small clouds” in the otherwise blue sky of late-19th-century science. The other was the failure to solve what came to be known as the *blackbody radiation problem*. In December of 1900, Max Planck announced a solution to this problem but only by assuming that the emission and absorption of electromagnetic energy, at the time believed to be continuous waves, could be only whole multiples of a discrete unit, or *quantum*, of energy. Thus was born *quantum theory*, but for the next 10 years, its “father” tried to smother it! In 1905, however, Einstein argued that light behaved as if it really *were* a stream of particles, characterized by a quantized amount of energy. In 1906–1908, he extended this quantum hypothesis to problems in physical chemistry, and others, too, found the quantum hypothesis valuable. In 1912, Niels Bohr rescued Ernest Rutherford’s so-called solar system model of the atom by quantizing the orbital energy of the electrons circling the atom’s central, positively charged nucleus. Suddenly, a wide range of puzzling phenomena could be explained but only by abandoning 19th-century conceptions of matter and energy.

Outline

- I. Radical as they were, the special and general theories of relativity are deterministic theories that use modes of reasoning and explanation, as well as forms of mathematics, that would have been familiar to 19th-century scientists.
 - A. The special and general theories of relativity leave in place the greatest achievements of 19th-century physics: the atomic theory of matter, the wave theory of light, and Maxwell’s electromagnetic theory of energy.
 - B. Quantum theory was far more radical than the special or general theories of relativity; it overturned the conceptual structure of 19th-century science. Quantum theory is important to examine because it changed both our ideas about physical reality and our conception of rationality itself.
 - C. We will look at the development of quantum theory in three stages.
 1. From 1900–1929 is the “heroic” period of quantum theory, encompassing Einstein’s 1905 paper to the formulation of quantum mechanics in 1925 and, after four years, to a radical interpretation of the physical meaning of quantum mechanics.

2. From 1930–1964 is the “working” stage, during which quantum theory was extended to a far more powerful theory, quantum electrodynamics (QED).
 3. Since 1964, quantum theory has been in its “mature” stage. This period has seen the replacement of QED with an even more powerful theory of matter, quantum chromodynamics (QCD), and the beginnings of the unification of all known forces of nature into a single theoretical framework.
 4. Running through all three stages is a foundational principle: that at the most fundamental level of natural processes, nature is discrete, not continuous. This principle applies even to space and time.
- II. Quantum theory begins with a problem that had puzzled physicists for two decades around the turn of the 20th century.
- A. A body that absorbs all the electromagnetic energy that falls on it, for example, all frequencies of light, is called a *blackbody*. As it absorbs this radiation, it becomes hotter, and the body itself begins to radiate. The question is: How is the energy radiated by the blackbody distributed among all the frequencies of electromagnetic radiation?
 - B. Physicists found equations that could predict the amount of energy radiated at low frequencies or high frequencies but could not find a single equation to cover both. The solution should have been found in a straightforward application of Maxwell’s electromagnetic theory.
 - C. In December 1900, Max Planck presented a paper that solved the blackbody radiation problem, but the solution came at a price. Planck’s solution rested on the assumption that electromagnetic energy could be emitted or absorbed only in discrete “packets” that he called *quanta* (later renamed *photons*). Further, quanta were restricted in size to whole multiples of a unit of energy; no intermediate values were permitted.
 - D. For the next 12 years, Planck attempted to amend his solution to eliminate the assumption of quanta, which contradicted Maxwell’s theory. In 1905, Einstein, in his paper on the photoelectric effect, accepted the existence of quanta as a fact of nature. He explained the photoelectric effect by arguing that light and, thus, all electromagnetic radiation, traveled through space as if it were a dilute gas, that is, as discrete, atom-like packets.
 - E. Between 1905–1909, Einstein applied the quantum hypothesis to solve a series of puzzling problems in physics and chemistry.

- III.** Einstein's 1905 paper on the photoelectric effect also raised another issue, which has been controversial ever since.
- A.** Einstein worked into this paper the claim that any serious theory of physics must be capable of giving a picture of reality.
 - B.** The general theory of relativity, for example, is a deterministic theory that gives us a picture of reality. According to Einstein, a physics theory must have a consistent conceptual structure; if a theory is conceptually inconsistent, it cannot be a true picture of reality.
 - C.** This notion would later place Einstein on the outside of further developments in quantum theory.
- IV.** Quantum theory came to the forefront of physics with the work of a young Danish post-doctoral student named Niels Bohr.
- A.** In 1911, Bohr won a fellowship to study at the Cavendish Laboratory at Cambridge with J. J. Thompson, the discoverer of the electron. But Bohr soon moved to the University of Manchester lab of Ernest Rutherford, who, in 1919, succeeded Thompson at Cambridge.
 - B.** As background to Bohr's work, we must first take a look at the development of the atomic theory of matter.
 - 1.** In 1806, John Dalton had defined the atom as solid and indivisible, but in 1896, J. J. Thompson discovered that atoms had an internal structure.
 - 2.** Thompson's discovery of an electrically charged particle inside the atom led to the question: How are these *electrons* organized inside the atom? Thompson proposed a model in which electrons were distributed in a positively-charged substance inside the atom, similar to raisins in pudding.
 - 3.** Between 1906 and 1910, a number of alternative models of the atom were suggested, including Rutherford's solar system model. This model was the result of an experiment in which thin sheets of gold were exposed to rays from radioactive material. Rutherford hoped to gain a clearer picture of the arrangement of electrons inside the gold atoms by observing how the positively charged alpha rays were deflected by the negatively charged electrons in the heavier gold atoms.
 - 4.** The surprising result of the experiment was that some of the alpha rays nearly bounced back, instead of passing through the gold foil. Rutherford proposed that atoms are not solid but, in fact, are mostly empty space. In Rutherford's understanding, the nucleus is a tiny fraction of the volume of an atom and is surrounded by a cloud of orbiting electrons.
 - 5.** This model has one major flaw: According to Maxwell's electromagnetic theory, the electron should instantly spiral into the

nucleus. There is no way for the negatively charged electrons to maintain a stable orbit around a positively charged nucleus. Rutherford's model seems correct experimentally but, theoretically, is totally wrong.

- C. At this point, fortuitously, Bohr came to Rutherford's lab and suggested applying the quantum hypothesis to the problem. Up to this time, the quantum hypothesis had been applied to electromagnetic energy. Bohr suggested using it to understand the mechanical energy of orbital electrons.
- D. Bohr postulated that orbital electrons do not radiate electromagnetic energy, even though they are negatively charged particles moving in the presence of a positively charged particle. They radiate only when they *change* orbits. Further, electrons can occupy only specific orbits around the nucleus of a given atom; in other words, their orbital energy is quantized.
- E. Using Bohr's assumptions, the atom becomes stable; further, the physical and chemical properties of atoms in the periodic table can be explained.
- F. Bohr's hypothesis also solved another profoundly puzzling problem of physics.
 - 1. Starting in the 1850s, scientists had discovered, using the spectroscope, that pure chemical elements, when heated until glowing, radiated light only at specific frequencies. Every element had its own "light print."
 - 2. Bohr's hypothesis explained why the elements behaved in this way. In every atom, there are specifically permitted and forbidden orbital transitions. When an electron changes its orbit and goes from a higher energy level to a lower energy level, it emits a photon of exactly the frequency corresponding to the loss of mechanical energy that the electron experiences.
- G. In our next lecture, we carry this heroic stage in the development of quantum theory into the 1920s, to its culmination in the Copenhagen interpretation of quantum mechanics.

Essential Reading:

George Gamow, *Thirty Years That Shook Physics: The Story of Quantum Theory*.

Barbara Cline, *Men Who Made the New Physics: Physicists and the Quantum Theory*.

Supplementary Reading:

Helge Kragh, *Quantum Generations: A History of Physics in the Twentieth Century*.

Questions to Consider:

1. Why was it so difficult for Planck to accept the reality of quanta, and why were Einstein and Bohr so willing to accept it?
2. How should our attitude toward scientific truth claims be affected by the reinterpretation of the established conception of physical reality forced by the relativity and quantum theories early in the 20th century?
3. What significance lies in the fact that the overwhelming majority of those who embraced the relativity and quantum theories were very young scientists, even graduate students, not their professors?

Lecture Four

The Heroic “Old” Age of Quantum Theory

Scope: The “old” quantum theory of 1900–1929, especially Bohr’s quantum theory of the atom (which, by 1922, was extended to a theory of the chemical elements), was rescued from problems that had arisen by two new forms of quantum theory: matrix mechanics and wave mechanics. These turned out to be mathematically equivalent and were highly successful experimentally, but as explanations of natural phenomena, they begged for interpretation. Niels Bohr and Werner Heisenberg played the leading roles in creating this interpretation, proposing fundamental changes in the conceptual framework of modern science that were made famous as the *uncertainty relations*, the *principle of complementarity*, and the *Copenhagen interpretation of quantum mechanics*.

Outline

- I. As mentioned in the last lecture, Bohr, through his quantization of the electron orbits inside an atom, rescued Rutherford’s solar system model of the atom.
 - A. The explanation of spectroscopic data that had been accumulated since 1850 gave credence to Bohr’s theory.
 - B. The fact that Bohr’s theory enabled the building up of the periodic table was also compelling evidence that the theory was accurate.
- II. The growth of Bohr’s quantum theory from 1912–1925 should not obscure its profound strangeness.
 - A. First, the theory attributes both particle-like characteristics and wave-like characteristics to electromagnetic energy, but waves and particles are mutually exclusive concepts.
 - B. The quantum hypothesis also pushes discontinuity deeper and deeper into nature.
 - C. Further, in 1917–1918, Einstein and Bohr convincingly argued that orbital transitions by electrons are random. Earlier, the disintegration of radioactive atoms had been shown to be random; this process had to be described statistically.
 1. Every radioactive element has its own distinctive disintegration rate (*half-life*), but the individual atoms in a radioactive element display a random pattern of disintegration.

2. The same is true of the orbital transition process. We cannot predict when an individual electron will change its orbit and either emit or absorb a photon.
 3. This randomness threatened the deterministic character of 19th-century science.
- D. The *correspondence principle* was yet another disconcerting feature of Bohr's quantum hypothesis. According to Bohr, even though the quantum theory fundamentally transforms classical physics, there is still a correspondence between the two.
- III. During the period 1920–1925, spectroscopic data, which had originally bolstered Bohr's hypothesis, suddenly became the enemy of quantum theory.
- A. Remember that the frequencies of light emitted by specimens were shown to be related to the orbital transitions permitted to electrons around a nucleus.
 - B. By 1922–1923, new spectroscopic experiments were being performed that called the quantum theory into question.
 - C. In 1923, Louis de Broglie, a French graduate student, wrote a paper predicting that matter, like electromagnetic energy, also has a dual character and may behave as both a particle and a wave.
 1. De Broglie's prediction was based entirely on mathematics, but in 1927, it was confirmed experimentally by two American physicists and, independently, two British physicists.
 2. In 1912, Max von Laue had suggested an experiment to demonstrate that X-rays were electromagnetic waves by showing their diffraction by a crystal. This same technique was adapted in 1927 to show that an electron beam was diffracted by a crystal just as X-rays were.
 - D. Scientists' understanding of matter had already been challenged with the discovery of radioactivity by Henri Becquerel in 1896 and Pierre and Marie Curie's isolation of radium in 1898. Now, physicists had to accept the idea that the wave-particle duality was not a curious fact about only energy, but about matter, as well.
 1. By 1910–1911, scientists knew that the products of radioactivity were alpha, beta, and gamma rays.
 2. As we mentioned, alpha rays are stripped helium atoms—combinations of two protons and two neutrons. Beta rays are actually electrons released when a radioactive nucleus splits. Gamma rays are extremely high-energy photons.
 3. Obviously, these discoveries painted a much more complicated picture of matter than scientists had previously seen.

- IV. Between 1923–1925, two physicists, working independently, developed new versions of quantum theory that resolved the spectroscopic crisis.
- A. Erwin Schrödinger, an Austrian physicist, based his theory on de Broglie's paper, not waiting for experimental confirmation. Schrödinger adapted some of the mathematical tools of the 19th-century wave theory of light to develop *wave mechanics*, a new quantum theory of electromagnetic energy that addressed spectroscopic questions of the early 1920s.
 - B. A few months earlier, Werner Heisenberg, a German physicist, also formulated a quantum theory that resolved the crisis but on what seemed to be totally different grounds.
 - C. Schrödinger's theory has an elegant, deterministic mathematical structure. In contrast, Heisenberg's theory was "ugly."
 - 1. Heisenberg developed his own version of matrix algebra, which operates with arrays rather than individual numbers.
 - 2. Heisenberg showed that by constructing matrices with spectroscopic data and applying the rules of quantum theory, the spectroscopic data can be explained; that is, the frequencies and energy levels of photons emitted by electrons in orbital transition can be predicted.
 - 3. Schrödinger later showed that his theory and Heisenberg's were mathematically equivalent. In 1926, the name *quantum mechanics* was given to this type of theory.
- V. By 1926, there was an empirically successful quantum mechanics of matter and energy, but its physical interpretation remained puzzling.
- A. Heisenberg's matrices violated an established rule of both physics and ordinary mathematics: that the order in which quantities were multiplied should make no difference in the result. This rule, *commutativity*, does not hold in matrix algebra or in Heisenberg's matrix mechanics. Why not?
 - 1. In 1927, Heisenberg interpreted the non-commutativity of his matrices as revelations of a deep truth about quantum-level reality: There is an inevitable uncertainty in our ability to collect information from the subatomic world.
 - 2. Heisenberg used the term *uncertainty relations* to assert the idea that there are limits to the precision with which we can know certain kinds of coupled facts about nature. For example, we cannot know both the exact position of a particle and its velocity. Interestingly, the uncertainty relations prevents our knowing just those facts that are required for a deterministic theory of nature!
 - 3. At first, Heisenberg's uncertainty relations seemed to illustrate the limits in humans' ability to gain information from nature.

Ultimately, however, the uncertainty relations were seen as facts about nature itself.

- B. Bohr responded to Heisenberg's uncertainty relations with two philosophical insights, the first of which was the *principle of complementarity*.
 - 1. Bohr argued that our ability to explain natural phenomena was constrained by our ability to form concepts. Our concepts come from experience, but we cannot directly experience photons. Inevitably, we must use complementary concepts, such as *wave* and *particle*, to explain the full spectrum of behaviors that nature reveals at a lower level than we can experience.
 - 2. This principle carries with it a blurring of the line between subjective and objective, between mind and world.
- C. In 1929, Bohr and Heisenberg collaborated on the second insight, the *Copenhagen interpretation of quantum mechanics*. This states that nature, at the most fundamental level, is probabilistic, not deterministic.

Essential Reading:

Abraham Pais, *Niels Bohr's Times: In Physics, Philosophy, and Polity*.

———, *The Genius of Science: A portrait gallery of twentieth-century physicists*.

Sam Treiman, *The Odd Quantum*.

Supplementary Reading:

Helge Kragh, *Quantum Generations: A History of Physics in the Twentieth Century*.

Questions to Consider:

- 1. Can scientists settle for the Bohr-Heisenberg view that theories describe human experience, not what's really out there and causing our experience?
- 2. The world we experience is highly orderly, continuous, and predictable, so how can the fundamental processes underlying experience be random and discontinuous?
- 3. Why do scientists "stick with" new theories that require deep conceptual change and pose serious problems they cannot initially solve, such as Rutherford's solar system model of the atom and Bohr's quantum theory of orbital electrons?

Lecture Five

A Newer Theory—QED

Scope: From 1929 on, quantum mechanics met the challenge of explaining a growing range of atomic phenomena, some of them its own predictions; some, the result of experiments with “atom-smashing” particle accelerators; and some, new discoveries, including the neutron, antimatter, cosmic rays, nuclear structure, and nuclear fission. The “old” quantum theory (1900–1925) was replaced in 1929 by quantum electrodynamics (QED), a quantum version of Maxwell’s electromagnetic theory consistent with the special theory of relativity. From 1929 through the 1950s, QED developed increasingly more comprehensive explanations of the interaction of matter and electromagnetic energy, but it remained an extension of wave/matrix mechanics and of the atomic theory of matter on which it rested. New instruments for probing the structure of the atom, however, began to force new theories of matter.

Outline

- I. In the past few lectures, we have discussed the “heroic” phase of quantum theory, starting about 1900 and climaxing around 1929 with the Copenhagen interpretation. As we move into the “working” phase of quantum electrodynamics (QED), we take a brief look at the progress of the theory.
 - A. Quantum theory had addressed a series of problems for physicists, such as blackbody radiation, the photoelectric effect, and the meaning of spectroscopic data.
 - B. The price that had to be paid for explaining these problems, however, was high. A number of longstanding scientific concepts were undermined or displaced by quantum theory.
 1. The first of these was the concept of causality. At the quantum level, events occurred that had no assignable cause. Quantum theory introduced randomness into fundamental natural processes.
 2. As we discussed, the concept of continuity was also undermined. Quantum theory insists that natural phenomena are discrete, not continuous.
 - C. In 1929, the British physicist P.A.M. Dirac incorporated the special theory of relativity into Schrödinger’s wave mechanics to arrive at a relativistic theory of the electron.
 1. In 1930, Dirac published a textbook that became a bible for physicists working in electromagnetics and electrodynamics. Thus, quantum electrodynamics (QED) became a framework for solving

- problems that involved the interaction of electromagnetic forces and material particles.
2. The time was ripe, then, for the integration of the earlier quantum theory into standard physics.
- II.** Dirac's new equations had a number of consequences that were startling, even by the standards of quantum theory.
- A.** The equations described the energy states of electrons but had negative solutions. Because Dirac believed that mathematics was capable of capturing the structure of reality, he did not discard these negative solutions. Instead, he posited the existence of antimatter; specifically, he predicted the existence of an electron with a positive charge, an anti-electron.
1. In 1932, the American physicist Carl Anderson discovered the anti-electron through his research into cosmic rays. He named this particle, which had roughly the same mass as the electron but the opposite charge, the *positron*. Anderson's discovery confirmed Dirac's bizarre prediction, which was derived only from mathematics, not from experimental research.
 2. In fact, P.M.S. Blackett and Guiseppe Occhialini, in Rutherford's laboratory at Cambridge, found the positron before Anderson, but they were not ready to announce the existence of such an extraordinary particle. Instead, they announced an equally amazing finding, seen in their cosmic ray emulsions: confirmation of Einstein's $E = mc^2$ in the conversion of photons into particles. Matter could be created out of energy.
- B.** Dirac's theory yielded a still more striking prediction: the zero energy state of an electron is, in fact, rich in virtual energy, which can manifest itself as photons.
1. Imagine an electron in an atom absorbing a passing photon, in the process jumping to a higher energy orbit. Later, the electron spontaneously returns to its previous orbit, emitting a photon of the same energy that it had earlier absorbed. Where did the photon come from?
 2. Dirac concluded that the absorbed photon continues to exist in a zero energy state, which has "room" mathematically for an infinite number of photons, and it emerges out of this state to a positive energy state when it is emitted. The vacuum, thus, is latently rich in mass-energy!
 3. Together with the uncertainty principle, Dirac's theory implied a new, dynamic conception of the vacuum, predicting the existence of negative vacuum energy states that would become central to cosmology in the 1980s in Alan Guth's inflation theory.

- III.** QED had a number of problems that were substantially resolved only after World War II.
- A.** One of these was that QED did not fully account for the special theory of relativity. The equations of quantum mechanics make predictions, involving changes in probability distributions, that seem to violate the special theory of relativity rule that no signal can travel faster than the speed of light in a vacuum.
 - B.** Further, some tension existed between the energy side of quantum mechanics and the matter side. The particle descriptions and the energy field descriptions did not completely mesh.
 - C.** Finally, the mathematics of Dirac's theory is replete with infinities, which physicists had to negate using an ad hoc process.
 - D.** Empirically, however, QED worked, and it became the framework for the theories that physicists used to identify and calculate the interaction of electromagnetic energy and matter.
- IV.** In 1932–1933, the attention of physicists began to focus on a problem *within* the atom.
- A.** QED had been primarily concerned with the interaction of orbital electrons and electromagnetic energy. The new focus on matter shifted the attention of physicists to gaining a better understanding of the nucleus.
 - B.** The first act in this rise of nuclear physics was the discovery of the neutron.
 - 1.** In the decade before the 1920s, scientists had realized that the combined mass of electrons and protons in an atom was lower than the mass of the atom. It was assumed that the nucleus must contain some electrically neutral substance that accounts for the missing mass.
 - 2.** In 1920, Rutherford postulated that the nucleus must be an electron-proton hybrid. This idea also explained the existence of beta “rays,” which are actually electrons, given off by radioactive atoms when they decay.
 - 3.** James Chadwick had been working in Rutherford's lab, trying to understand the range of energies given off by the electrons in beta decay. Chadwick insisted that the spectrum of energies was continuous, contrary to quantum theory, and over the course of the 1920s, experimental evidence seemed to support this conclusion.
 - 4.** In the late 1920s, Bohr, to maintain discreteness and rescue quantum theory, saw the need to give up the long-standing principle of the conservation of energy. Oddly enough, many of the leading physicists of the day were prepared to go along with Bohr.

5. Wolfgang Pauli, however, one of the architects of quantum mechanics in the 1920s and of QED in the 1930s, proposed an alternative: that there was an electrically neutral particle of about the same mass as the electron in the nucleus that was expelled, along with the electron, in beta decay; its energy, together with that of the electron, satisfied the requirements of conservation. Subsequently, Enrico Fermi called this particle a *neutrino*.
- C. At the same time, in the early 1930s, Chadwick repeated some experiments reported in Germany and France in which particles were fired at samples of beryllium. Chadwick showed conclusively that the beryllium was converted to carbon with the release of a particle called a *neutron*.
- D. A new theory of beta decay was proposed by Enrico Fermi in 1934: A neutron in a radioactive nucleus spontaneously turns into a proton and an electron, along with a neutrino.
 1. Neutrinos remained undetected until 1955. Although they are the most numerous particle in the universe, they are extremely elusive.
 2. Neutrinos were originally thought to be without mass and electrically neutral, but they are now known to have an extremely small mass and to exist in three forms.
- E. At this point in history, QED has set the stage for the emergence of nuclear physics, which we will discuss in the next lecture.

Essential Reading:

Helge Kragh, *Quantum Generations: A History of Physics in the Twentieth Century*.

Silvan Schweber, *QED and the Men Who Made It: Dyson, Feynman, Schwinger, and Tomonaga*.

Sam Treiman, *The Odd Quantum*.

Questions to Consider:

1. Mathematical equations can summarize experimental data, but how can they predict new aspects of reality, as with Dirac's anti-electron?
2. With respect to the threat to quantum theory posed by Chadwick's explanation of beta decay in 1930 and Bohr's and Pauli's responses, how do scientists know when to give up a principle believed to be fundamental, like conservation of energy; when to modify a theory to protect the principle; or when to give up a theory as wrong because it conflicts with the principle?
3. What does it tell us about scientists' commitment to their theories that QED, a theory based on an intimate connection between mathematics and reality, was rescued from a serious mathematics-based problem by the

“trick” called renormalization?

Lecture Six

QED Meets Fission and Fusion

Scope: The history of nuclear fission is dominated, and distorted, by the understandable fascination with the atom bomb, as the story of fusion is by the hydrogen bomb. The broader story of fission, however, is even more fascinating. Recognition of the reality of fission and, with it, the possibility of the transmutation of elements, had to overcome deep resistance to what seemed to many physicists and chemists a revival of alchemy. What was at stake was the very concept of an element, a truly fundamental building block of the world. The history of fission is a chapter in the story of the discovery of the complex internal structure of the atom, revealing a dizzying world of subatomic particles. Another chapter in that story is the development of “atom-smashing” machines that provided the theorists with startling new data.

Outline

- I. We ended the last lecture with the discovery of the neutron and the development of a satisfying theory of beta decay.
 - A. The discovery of the neutron focused the attention of physicists on the nucleus and resulted in a three-particle theory of matter. How, then, were the protons and neutrons arranged in the nucleus, and what forces hold the nucleus together?
 - B. These questions defined the field of nuclear physics in the mid-1930s. At the same time, a number of lines of inquiry, such as radioactivity, fission, and QED, began to converge.
- II. One important theory, developed in the mid-1930s, was that protons and neutrons were arranged in concentric shells in the nucleus, just as electrons were arranged in concentric orbits around the nucleus.
 - A. In 1937, Hideki Yukawa, a Japanese physicist, proposed that the nuclear particles were bound by *weak* and *strong* interactions, or *forces*. In quantum theory, every force must have a carrier. For example, the carrier of the electromagnetic force is the photon. Thus, Yukawa also predicted the existence of a short-lived nuclear particle, a *mesotron* or *meson*, that was soon “found” in cosmic ray experiments.
 - B. Yukawa’s work was an expression of the attempts to work out a theory of the nucleus that would be consistent with the growing body of experimental evidence about radioactivity and the ability of atoms to undergo fission.

- III.** From 1930 on, physicists used QED for a specific task, that is, to calculate the probability that an atom will absorb or scatter a particle that approaches it.
- A.** In scattering experiments, charged particles are “fired” at a target and the angles through which they are deflected are carefully measured. From the mass and energy of the beam particles, inferences can be made about the internal structure of the target atoms.
 - B.** In absorption experiments, the objective is to observe what happens when a nucleus absorbs, rather than deflects, a beam particle. The result must be some fundamental change in the nature of that atom. If the atom absorbs a neutron, it could simply become an isotope of itself, or it could become unstable and split.
 - C.** This context, of applying QED to the understanding of fission, occupied scientists in the period 1934–1939. At the time, physicists focused their research on uranium.
 - 1.** Uranium-235 was sensitive to slow neutrons. QED allowed scientists to calculate the probability that uranium-235 atoms would absorb a neutron, undergo fission, and release neutrons, as well as energy.
 - 2.** The released neutrons would then trigger a chain reaction of fission in other uranium atoms, resulting in a tremendous amount of energy in a short period of time*.
 - D.** This process was beginning to be understood by the end of the 1930s, and hundreds of scientists around the world were involved in a surge of nuclear physics research.
 - 1.** Key roles were played by Enrico Fermi in Italy and by Lisa Meitner and her long-term partner, Otto Hahn, in Germany. By 1939, all the “pieces” for releasing atomic energy were in place, and with the outbreak of World War II, the development of an atom bomb became inevitable.
 - 2.** Niels Bohr played a small but essential role in the calculation of the absorption coefficient, which told scientists whether it would be possible for a small amount of the isotope uranium-235 to create the fission reaction required for a bomb.
 - 3.** Heisenberg was the head of the German atomic bomb project in World War II. He seems to have mistakenly concluded that too much uranium would be needed to construct a weapon that could be carried in an airplane.
 - 4.** In 1940, President Roosevelt created the National Defense Research Council (NDRC) to organize the nation’s academic scientists as a resource in the event of war. Later, the NDRC became the Office of Scientific Research and Development. One of its first projects was to authorize Enrico Fermi to build a small

nuclear reactor to test Bohr's QED calculation of neutron absorption by uranium nuclei.

5. The Manhattan Project, led by the United States and directed by physicist J. Robert Oppenheimer, was created in late 1942. By 1944, most of the physics was done, and building the bombs was primarily an engineering challenge.

- IV. Fission was only one track that nuclear research followed in the 1930s. Concurrently, a group of physicists began to explore fusion: the possibility of fusing protons together to build elements from the bottom up, rather than breaking them apart via fission.
- A. Hydrogen atoms are the "easiest" atoms to fuse because they are the simplest atoms.
 1. Fusing four hydrogen atoms results in one helium atom, but the energy required to achieve fusion is enormous.
 2. The hydrogen, for example, would have to be heated to approximately the same temperature as the core of the Sun, over 15 million degrees, and compressed. The difference in mass between the resulting helium atom and the four hydrogen atoms would manifest itself as energy.
 - B. In 1938, Hans Bethe formulated a fusion-based theory of how stars produce their energy that finally gave us an understanding of how the universe is structured.
 1. As a star collapses gravitationally, if it has enough mass, it will eventually become hot enough at the center to ignite a fusion reaction. That reaction will convert hydrogen to helium for as long as hydrogen is present.
 2. When the hydrogen runs out, the star begins to collapse again, and its temperature increases again. Eventually, the helium begins to fuse into more complicated atoms.
 3. At some point, the star can no longer resist gravitational collapse and explodes, spewing a complex combination of atoms created through the fusion process into interstellar space.
 - C. In 1939, George Gamow speculated that Bethe's theory of how stars generate their energy explained the origin of the universe in his *Big Bang theory*.
 - D. In the course of the atomic bomb project, Edward Teller, a Hungarian physicist working in Los Alamos, argued that an atomic bomb could be used as a trigger to explode a hydrogen bomb.
 1. Immediately after the war, Oppenheimer and many of the physicists who had worked on the atomic bomb project were quite frightened by what they had created.

2. Teller, however, received Truman's approval to design a hydrogen bomb and did so with crucial assistance from Stanislaw Ulam, a Polish mathematician.
3. Teller also denounced Oppenheimer as a security risk, leading to a scandal that rocked the American physics community.

Essential Reading:

Daniel Kevles, *The Physicists: The History of a Scientific Community in Modern America*.

Helge Kragh, *Quantum Generations: A History of Physics in the Twentieth Century*.

Supplementary Reading:

Mary Jo Nye, *Before Big Science: The Pursuit of Modern Chemistry and Physics, 1800–1940*.

Questions to Consider:

1. With the broad publication of research in nuclear physics from 1935–1939, was the atomic bomb inevitable? Was the hydrogen bomb? Is any application of a scientific theory?
2. Why has access to fission and fusion energy proven so problematic for us, given our long experience with the controlled release of chemical energy?
3. What insights into conceptual creativity can we derive from George Gamow's radical ideas of quantum "tunneling" in 1930 (see the next lecture) and the origin of the universe in 1939?

* *Clarification:* Slow neutrons do have an unexpectedly large probability of being captured by U-235 and U-238 nuclei, and this is key to the controlled fission of U-235 atoms in a nuclear power reactor, for example, and to transforming U-238 atoms into Plutonium-239. But only fast neutrons, with a lower capture probability, can generate the rapid chain reaction required by an atomic bomb.

Lecture Seven

Learning by Smashing

Scope: We return to QED in the 1930s and a survey of the experimental world that drove theory by building new kinds of machines that revealed aspects of matter and energy utterly unanticipated before the 20th century. The “atom-smashing” machines themselves are the “stars” of this part of the story.

Outline

- I. A problem common to all atomic physicists in 1930 was the lack of a source of high-energy particles with which to bombard atoms of target materials, “smashing” them in order to see what they were made of.
 - A. As early as 1919–1920, Ernest Rutherford had been calling for the invention of a machine that would provide a focusable beam of charged particles with which to “smash” target atoms. Radioactivity is not the optimal tool to use for this form of experimentation.
 - B. The unit that physicists use to discuss the energy of particles is the *electron volt (ev)*. The energy equivalent of the mass of an electron is about 500,000 ev; that of a proton is about 1000 Mev.
 - C. Around 1930, John Cockcroft and Ernest Walton, in Rutherford’s lab, designed an electrostatic proton accelerator, which resembled something out of an early science fiction film.
 - 1. This device built up significant charges of electrical energy and generated a spark, then accelerated those particles to achieve modest energies, initially less than 400,000 ev.
 - 2. In 1930, George Gamow published a textbook in which he identified a peculiar consequence of quantum mechanics. According to quantum theory, there is a small but nontrivial probability that a weak particle can get past an energy barrier in a phenomenon called *tunneling*. Thus, a proton accelerating at only 400,000 ev could tunnel into a nucleus.
 - D. Several years earlier, Merle Tuve and Gregory Breit at the Carnegie Institution of Washington, D.C., built a particle accelerator that achieved 1 Mev, but the beam was too weak to be useful for research.
 - E. In the early 1930s, Ernest O. Lawrence of the University of California at Berkeley emerged as the atom smasher *par excellence*.
 - 1. Lawrence adapted a design for a particle accelerator, called a *cyclotron*, from an idea proposed by a European electrical engineer, Rolf Wideröe. This device worked by periodically boosting a charged particle to accelerate it to higher and higher speeds.

2. The design took advantage of a principle called *resonance*, which is one of the most fundamental insights into nature achieved by modern science. *Resonance* is the selective transfer of energy between objects by exploiting periodicity.
 3. The principle is similar to pushing a child on a swing. If you push gently but repeatedly at just the right moment, the heavy swing goes higher and higher.
 4. It is because of resonance that all the C strings on the sounding board of a properly tuned piano vibrate when any one of them is struck, while the D string immediately adjacent to the struck C string does not vibrate at all.
 5. Similarly, a radio or a TV receiver selectively absorbs and amplifies only the electromagnetic waves to which it is tuned, ignoring the myriad others that wash over the receiver's antenna.
 6. The concept of resonance is central to any wave-like or periodic phenomenon.
- II.** In 1930, as a new Berkeley assistant professor, Lawrence directed two graduate students, David Sloan and M. Stanley Livingston, in building two different types of cyclotrons.
- A.** Lawrence's first machine was only 5 inches in diameter. Charged particles were injected at the center of this 5-inch disk and spiraled out to its circumference. The particles were periodically boosted with an electrical signal to accelerate them to higher velocities. The output was only 80 Kev.
 - B.** In 1932, the team of Lawrence, Livingston, and Sloan scaled up the cyclotron to 11 inches and achieved 1 Mev.
 - C.** By 1939, Lawrence's lab had a 60-inch-diameter cyclotron and had achieved a 10-Mev beam. The team also had a Rockefeller Foundation promise of \$1.4 million to build a 184-inch machine that would reach 100 Mev. This accelerator was ultimately co-opted by the war effort.
 1. Using the cyclotron at Lawrence's lab, Glenn Seaborg discovered the element plutonium, which was found to be, like uranium, ideally suited for the release of nuclear energy.
 2. The cyclotron principle could also be used to separate weapons-grade uranium-235 from naturally occurring uranium-238.
 - D.** At the end of the war, Lawrence's design was found to be flawed, because it did not take into account the special theory of relativity: As particles begin to approach a significant fraction of the speed of light, they behave as if they have enormous masses. More and more energy is required, then, to accelerate the particles further. The design of the cyclotron would have to be modified.

- III.** In 1946, a significant design advance led to retrofitting the 184-inch Berkeley cyclotron as a 195-Mev synchro-cyclotron, a machine that generated pulses of protons rather than a continuous beam.
- A.** Synchrotrons were able to create mesons in the lab. Suddenly, scientists were free from their dependence on cosmic rays to reveal the presence of mesons.
 - B.** But cosmic rays were soon discovered to produce heavier particles than mesons, and more powerful machines were needed if the lab were to serve as a substitute for nature.
 - 1.** In 1952, at Brookhaven National Laboratory, a further design advance resulted in a 3-Gev (3 billion ev) machine called a Cosmotron. This device eliminated the spiral path of the cyclotron and kept the beam of charged particles traveling in a circle using powerful magnets. At two intervals in the circular path, the particles are given a pulse of energy to accelerate them further.
 - 2.** The Cosmotron was followed by a 6.2-Gev machine at Berkeley in 1954, called the Bevatron. This accelerator enabled discovery of the anti-proton, which had been predicted by Dirac in 1930.
 - 3.** The design of the Bevatron also opened the way to much higher energies by colliding contra-rotating beams: A prototype colliding-beam machine was built in 1965 as a Princeton-Stanford collaboration. This design became the standard in constructing particle accelerators.
- IV.** Before we close, we must note that particle accelerators are useless without detectors and information processing.
- A.** Luis Alvarez built a 72-inch bubble chamber as a detector for the Bevatron. It required a 3-million-watt power supply of its own. For the linear accelerator at Stanford, David Nygren worked for 10 years to build the time projection chamber, which is now standard equipment for all large particle accelerators.
 - B.** Further, a typical particle accelerator “run” generates millions of events and vast quantities of data that must be analyzed by powerful computers.
 - C.** A global particle accelerator race took place in the 1960s–1970s that pushed accelerator sizes and energies higher and higher. In the 1980s, FermiLab in the United States and the European Center for Nuclear Research (CERN) each had particle accelerators in the Tev (1 trillion ev) range. In late 1993, the United States essentially bowed out of the race when Congress cancelled funding for the Superconducting SuperCollider.
 - D.** In 2002, CERN began an upgrade of its 1-Tev accelerator to a 7-Tev machine with a circumference of 27 km. This device will be just

capable of “seeing” the Higgs boson, which we will discuss in a later lecture.

Supplementary Reading:

Luis Alvarez, *Alvarez: Adventures of a Physicist*.

Frank Close, et al., *The Particle Odyssey: A Journey to the Heart of the Matter*.

Helge Kragh, *Quantum Generations: A History of Physics in the Twentieth Century*.

Questions to Consider:

1. Is there a kind of logical circularity implicit in using complex instruments designed in accordance with a theory to discover new realities independent of that theory?
2. Do powerful particle accelerators reveal reality or create artificial realities that reflect their own operation?
3. Why has the public in the United States and Western Europe, for more than 50 years, supported the very high costs of building and operating increasingly expensive particle accelerator-based research?

Lecture Eight

What Good Is QED?

Scope: Between 1929, when Dirac laid the foundation for QED, and 1964, when Gell-Mann and Zweig laid the foundation for its successor, quantum chromodynamics, quantum mechanics was intensively “used” as a theory in chemistry, as well as in physics. It guided the development of nuclear and subatomic physics and anchored a new theory of matter and the complex structure of nuclei. It played a central role in the theory and the application of fission and fusion. But it also played a central role in areas of physics and chemistry that, after World War II, drove technological innovations that transformed societies worldwide, among them, computers and lasers. In addition, QED became the basis for a new theory of chemical bonding that, by 2000, was fundamentally changing how chemists thought and worked and what they could do with matter and energy.

Outline

- I. As we close our study of the “working” period of QED, we will take a look at its practical applications, as well as some philosophical issues that surrounded it. What was the quantum theory of the 1930s–1950s good for?
 - A. Science has become a big-budget, heavily politicized institution, but its ultimate goal is still to understand natural phenomena. The goal of QED, at the deepest level, is to help us understand the ultimate constitution of matter and the relationship between matter and energy. The more specific goal is to identify a single comprehensive theory of matter and energy.
 - B. QED does not yield this comprehensive theory. It gives us insight into the electromagnetic force but does not encompass the strong and weak forces or the force of gravity. A *theory of everything* (TOE) will unify these forces in one overall explanation.
 - C. In the 1960s–1970s, as the Big Bang theory started to receive support among scientists, the atom smashers that had been built in the preceding years were recognized as time machines. These devices re-created conditions that existed in the universe in the first few moments after its violent birth.
 1. At that time, the total energy level of the universe was greater than the energies that we can replicate in any existing particle accelerator.
 2. The CERN accelerator that we discussed in the last lecture may be able to replicate conditions at about 10^{-12} seconds after the birth of the universe, when the Higgs boson existed.

3. Particle accelerators are not used merely to destroy atoms and examine the resulting bits and pieces. They allow us to infer important information about the universe in which we live.
- II.** QED provoked a decades-long philosophical debate between Albert Einstein and Niels Bohr.
- A.** From 1929–1953, Einstein and Bohr, along with many other scientists, engaged in a dialogue about the nature of the relationship between science and reality. What is the object of scientific theories?
 1. According to Bohr, scientific theories tell us about our experience. According to Einstein, they tell us about an independently existing, external reality.
 2. Einstein believed that our scientific theories “lift a corner of the veil” that separates us from seeing reality. Bohr believed that we can never lift the veil; we can interpret reality using only the concepts that come to our minds based on our experience.
 - B.** Einstein and Bohr also debated the principle of causality. Bohr believed that there is no causal theory of nature below the quantum level. Einstein recognized that quantum theory was accurate, but he believed that a causal and deterministic level lay underneath the predictions of quantum theory. Most physicists sided with Bohr.
 - C.** Finally, a third issue between Bohr and Einstein was whether the special theory of relativity was of universal applicability.
 1. Remember that the special theory of relativity states that no signal can travel faster than the speed of light in a vacuum, but quantum theory seems to allow some kind of physical influence to propagate instantaneously.
 2. Imagine that we measure the position of an electron at time 0. Then, we use quantum theory to calculate the probabilities for the position of the electron a short period of time later.
 3. According to our results, there is a non-zero probability that the electron is near Jupiter, but according to the special theory of relativity, the electron cannot be near Jupiter because it cannot travel faster than the speed of light.
 4. Whether these probability functions can be physically interpreted has been controversial since the mid-1920s.
 - D.** In 1935, Einstein co-authored a paper asserting that, according to quantum theory, a situation could exist in which one particle could influence another particle instantaneously. Einstein believed that this situation was absurd and, therefore, quantum theory was incomplete.
 1. In the early 1950s, the Irish physicist John Bell reduced Einstein’s thought experiment to an inequality equation. Thirty years later, a French physicist, Alain Aspect, translated Bell’s inequality into a lab experiment and proved that quantum theory is correct: An

influence on one of two particles created at the same time can have an instantaneous impact on the second particle.

2. In the year 2002, a team of physicists at the University of Vienna demonstrated a device based on this experiment that transmitted a quantum-encrypted signal across the River Danube.

III. We now turn from the philosophical to important practical applications of QED.

- A. As early as 1927, a number of the physicists who created quantum mechanics began applying it to the behavior of electrons in metals. In 1929, Felix Bloch, a student of Heisenberg's, discovered that in a material with a lattice structure, the energy states of the electrons were not the discrete states associated with orbital electrons, but a discrete set of continuous "bands" of energies.
 1. In 1931, Alan Wilson, a British physicist studying with Bloch and Heisenberg, applied Bloch's band theory to semiconductors, characterizing them as insulators with a band gap that suitably excited electrons could cross. Others found that semiconductors came in two types—called *p-type* and *n-type*—and that odd things happened to currents at their junctions with one another.
 2. In December of 1947, William Shockley, Walter Brattain, and John Bardeen, extending Wilson's semiconductor theory, created the first primitive transistor using a germanium crystal. In 1948, the improved device, using silicon, would revolutionize electronics and enable the computer age.
- B. In 1917 and 1918, Einstein and Bohr established the randomness of the emission and absorption of light quanta by individual orbital electrons.
 1. In 1950, experiments showed that it was possible to "pump" electrons in certain substances "up" to an unstable, high-energy orbit around their nuclei, after which they spontaneously "fell" all at once to the same lower level, in the process emitting photons of exactly the same frequency because each had the same energy. Such a single-frequency beam of photons is called *coherent*.
 2. In 1951, Columbia University professor Charles Townes put all these ideas together with his own idea of enclosing the substance he used, ammonia gas, in a resonant cavity. His invention successfully generated coherent beams of high-frequency microwave radiation, but it also, thanks to the resonant cavity, amplified them. Townes called the device a *maser*, short for "microwave amplification by the stimulated emission of radiation."
 3. In 1958, Townes and Bell Labs physicist Arthur Schawlow published a detailed analysis of "optical masers," shortly after dubbed *lasers*, but it was a Hughes Research Labs physicist,

Theodore Maiman, who built the first laser, using ruby crystals, in 1960.

- C. Another application of QED is superconductivity, the complete disappearance of electrical resistance in a conductor at extremely low temperatures, typically between 4 and 8 degrees Kelvin.
 - 1. Explaining superconductivity turned out to be more difficult than expected, but in 1957, building on earlier ideas, John Bardeen, John Schrieffer, and Leon Cooper developed a quantum theory of ultra-low-temperature (below 30 degrees K) superconductivity that matched the experimental data and made predictions that were confirmed.
 - 2. Medical, military, and research applications followed, among them the superconducting magnets at FermiLab and CERN that dramatically increased accelerator beam energies.
- D. We will look at the applications of QED in chemistry in another lecture, but here we should note the quantum mechanics–based theory of chemical bonds worked out by Linus Pauling, which in principle, allows scientists to calculate chemical reactions in advance of their occurrence.

Essential Reading:

Amir Aczel, *Entanglement: The Greatest Mystery in Physics*.

John Gribbin, *Schrödinger's Kittens and the Search for Reality*.

Abraham Pais, *Subtle Is the Lord: The Science and the Life of Albert Einstein*.

Questions to Consider:

- 1. Does the value of a scientific theory that improves our understanding increase because it has practical applications?
- 2. Was Einstein simply stubborn in refusing to accept the probability interpretation of quantum mechanics, or was he justified by the importance of the world view he was defending?
- 3. What must reality be like if the universe is internally connected in the ways suggested by Alain Aspect's photon entanglement experiments?

Lecture Nine

The Newest Theory—Quantum Chromodynamics

Scope: By the 1960s, the number of “elementary” subatomic particles created by ever-more powerful particle accelerators was in the hundreds and the need for a unifying theory was pressing. Concurrently, new experiments suggested the need to extend QED to explain new phenomena. The result was a quantum theory of matter and energy, named *quantum chromodynamics (QCD)*, which reduced all material particles to one of two elementary types and dropped protons and neutrons from the ranks of elementary particles. Electrons survive as elementary particles, now as members of a family of six particles called *leptons*, three carrying whole negative electric charges, each with its own type of neutrino. Protons, neutrons, and the host of once “elementary” particles are members of a family called *hadrons* and are composed of various combinations of six truly elementary particles called *quarks* and *anti-quarks*, bound by mass-less particles called *gluons*. The story of QCD is fascinating even by the standards of quantum theory!

Outline

- I. In the late 1940s, Schwinger, Feynman, and Tomonaga, working independently, had put QED on a much firmer mathematical foundation, accounting for the infinities found in mathematical calculations of the theory through *renormalization*.
 - A. In 1953, Abraham Pais and Murray Gell-Mann reviewed the state of quantum theory and reached the conclusion that four forces seemed to be responsible for all physical phenomena at the most fundamental level of nature: the gravitational force; the electromagnetic force; the *weak* force associated with nuclear processes, such as the decay of the neutron into a proton, electron, and neutrino; and the *strong* force that held the nucleus together. Unifying these forces with one theory became a goal for physics in the late 1950s.
 - B. At this point, physics had a theory of the electromagnetic force, namely, QED, as well as a patched-together theory of the weak force, covered by Fermi’s theory of beta decay. The gravitational force was not considered at the atomic level, but still, physics did not have a theory to explain the strong force.
- II. In the late 1950s and early 1960s, because of the explosive growth in the power of particle accelerators, the number of “elementary” particles had reached more than 200, which seemed ridiculous to physicists.

- A. Murray Gell-Mann and, independently, Israeli physicist Yuval Ne'eman devised an elegant system for organizing these particles into eight families. Gell-Mann called this system the *Eightfold Way*, after the Buddhist doctrine of virtue.
 - B. Gell-Mann and Ne'eman predicted the existence and properties of a particle that had not yet been detected; this particle would be the last member of one of their 10-member particle families.
 - C. A short time later, the particle was found in the Cosmotron accelerator at Brookhaven National Laboratory. Gell-Mann named the particle *omega*, after the biblical reference to God as first and last, in Greek, as *alpha* and *omega*.
- III. Between 1962 and 1964, Gell-Mann at Caltech and, independently, George Zweig at CERN, proposed a new theory of the strong force, in which protons and neutrons are not elementary particles.
- A. From the 1930s, physicists already knew that the neutron is, at best, an unstable particle, because it disintegrates outside the nucleus. In the 1960s, particle accelerators, especially the linear accelerator at Stanford University (SLAC), were “smashing” electrons into protons, and the protons were also disintegrating!
 - 1. The Gell-Mann/Zweig proposal was that matter is composed of two types of particles: *leptons*, the family of particles to which electrons and neutrinos belong (which respond only to the electromagnetic and weak forces), and *hadrons*, which is the family that includes everything else. All hadrons are made of combinations of *quarks*. Quarks are held together by *gluons*, of which there are eight.
 - 2. In 1964, the mathematician Oscar Greenberg realized that gluons had to be categorized into one of three different *color charges*.
 - B. Initially, Gell-Mann proposed three quarks, named *up*, *down*, and *strange*.
 - 1. The up and down quarks, together with electrons, fully account for the behavior of ordinary matter in ordinary physical and chemical interactions.
 - 2. When the energy levels get high enough, however, such as in stars, black holes, cosmic ray collisions, and at the birth of the universe, then strange quarks come into play.
 - C. The apparent whimsicality of the names in this new theory, *quantum chromodynamics* (QCD), is a deliberate attempt to avoid a problem that plagued “old” quantum theory and QED. Applying classical-physics names to quantum-level descriptions unconsciously led to thinking classically and inappropriately about quantum-level phenomena classically. Whimsical names force a recognition that the quantum level of reality is beyond our experience.

IV. Quarks are peculiar particles.

- A. Quarks have mass, *spin*, and fractional charge. Quarks and anti-quarks, unlike matter and antimatter, combine constructively, not destructively. Quarks are also *much* smaller and *much* lighter than protons and neutrons. Where, then, does their mass come from?
 - 1. Quarks move so rapidly that relativity comes into play, and particles made of quarks—protons, for example—seem to have more mass than they actually do.
 - 2. We must uncouple, in our minds, the concepts of mass and solidity.
- B. In 1973, Burton Richter at SLAC and Samuel Ting at Brookhaven independently discovered a fourth quark, named *charm*. In 1977, Leon Lederman at FermiLab discovered a fifth, named *bottom*. QCD required that if there were five quarks, then there must be a sixth, which would be called *top*.
- C. It took 18 years and major upgrades to the particle accelerators at FermiLab and CERN to discover the top quark. By 1995, the accelerator at FermiLab had reached 1.8 TeV.
 - 1. The team at FermiLab had to examine 16 million collision events to identify a handful of top resonances. Although the results were announced in 1995, the data had been collected two years earlier.
 - 2. It is worth noting that the FermiLab team involved in this discovery consisted of 440 physicists, mathematicians, computer scientists, and engineers from 35 institutions in a dozen countries.
- D. The announcement of the top quark in 1995 completed QCD. From 1964, when this theory of the strong force was first proposed, to the end of the 20th century, the theory has resisted all challenges that have been mounted against it.
 - 1. This is not to say that QCD is without problems. For example, the question of whether or not the neutrino has mass has provoked some controversy, and QCD has been unable to explain the fact that this particle does, indeed, have some mass.
 - 2. Nevertheless, by the end of the 20th century, QCD could be used as a platform on which to attempt unification. As we will see in our next lecture, this attempt had actually begun in the 1960s, in parallel with the development of QCD.

Essential Reading:

Murray Gell-Mann, *The Quark and the Jaguar: Adventures in the Simple and the Complex*.

Andrew Pickering, *Constructing Quarks: A Sociological History of Particle Physics*.

Martin Rees, *Just Six Numbers: The Deep Forces That Shape the Universe*.

Supplementary Reading:

Helge Kragh, *Quantum Generations: A History of Physics in the Twentieth Century*.

Questions to Consider:

1. Who decides how many particles can be “elementary” and on what grounds?
2. What lessons are there in the whimsical names used in QCD for how our thinking can mislead us when reasoning about new situations?
3. We’ve seen how mathematics can reveal new aspects of physical reality, but how can simple classification schemes, like the Gell-Mann/Ne’eman Eightfold Way (or Mendelev’s periodic table), have predictive power?

Lecture Ten

Unifying Nature

Scope: Between 1964 and 2000, three of the four fundamental natural forces identified by Pais and Gell-Mann as implicit in QED were successfully united in what is called the *standard model* of quantum theory, which links physics today to the physics of the early universe. The fourth force, gravity, has resisted integration into a single theoretical framework with the other three. Physicists are pursuing the unification of the general theory of relativity and the Standard Model into a quantum theory of gravity. In the process, models of nature have been generated that seem too fanciful even for science fiction but are highly provocative intellectually: for example, suggesting that our conception of the universe today may be as narrow as Copernicus's was in his time or that the entire vast universe derives from a "pocketful" of negative vacuum energy and is an information structure!

Outline

- I. This lecture explores the attempts in the last decades of the 20th century to unify the theories explaining the four fundamental forces of nature.
 - A. The goal of these attempts is to unify the forces in a way that is physically real. Physicists are trying to trace these four forces back to a single "mother force" in the universe that underwent a series of collapses, resulting in the strong, weak, electromagnetic, and gravitational forces.
 - B. An analogy can be made with steam, which as a gas, operates under a certain set of laws. As the steam cools, it becomes water, which operates under a different set of laws. If the water cools further, it may freeze and become ice, operating under a third set of laws.
 - C. Unification theorists are looking for a single original force in the universe that has undergone similar *phase transitions* to become the four forces that we know today.
 1. At some point, it is postulated that the universe had a certain high energy level operating under the laws of a single force. Then, as the universe cooled, it went through a series of phase transitions and the forces that we know today "froze out."
 2. For example, gravity separated at approximately 10^{-43} seconds after the Big Bang, but the other forces were still subsumed under the single force.
- II. In the 1950s, Schwinger, Pakistani physicist Abdus Salam, and British physicist John Ward tried to unify the weak and electromagnetic forces.

- A. QED—the theory of the electromagnetic force—and the weak force are natural allies because they are both associated with electrons. This first attempt at unification, however, was premature and did not succeed.
- B. In 1961, Harvard physicist Sheldon Glashow revisited the work of Schwinger, Salam, and Ward and creatively reformulated it to predict the existence of a carrier of the weak force.
 - 1. As we've discussed, in quantum theory, every force must have a carrier. The photon, for example, is the carrier of the electromagnetic force. The gluon is the carrier of the force that holds hadrons together. The *graviton* is the projected carrier of the gravitational force.
 - 2. As the carrier of the weak force, Glashow proposed a family of three particles called *intermediate vector bosons (IVBs)*. One would have a positive charge, one would have a negative charge, and one would be electrically neutral; all three would have mass.
- C. Over the next 10 years, this unification approach was developed further by Glashow and the American Steven Weinberg, by Salam, by the British physicist Peter Higgs, and by the Dutch physicist Gerardus t'Hooft. Glashow, Salam, and Weinberg used three concepts in particular for their formulation of the *electro-weak theory*, for which they shared a Nobel Prize.
 - 1. The first of these is a mathematical requirement of scale, or as it is called *gauge*, invariance, introduced in 1918 by Herman Weyl in an unsuccessful attempt to unify the general theory of relativity and classical electrodynamics. As a rule, when the scale changes in an equation, the laws of physics do not change. Unification theories are required by physicists to be scale invariant.
 - 2. The second technique used by Glashow, Salam, and Weinberg was a 19th-century abstract mathematical invention called *group theory*. Unification theorists invent groups with mathematical properties that parallel the physical relationships that would solve their problems, then look at the empirical data to see if they fit!
 - 3. The third concept used by unification theorists is *spontaneous symmetry breaking*.
 - a. At its most fundamental level, nature is assumed to be simple and symmetrical. Asymmetries arise because something has disturbed the underlying symmetry.
 - b. In 1961, the Japanese physicist Yoichiro Nambu postulated spontaneous symmetry breaking in an attempt to develop a new theory of superconductivity. Weinberg and Salam incorporated this idea into electro-weak unification. In this view, photons and IVBs become the asymmetric “debris” of the collapse of an earlier force.

- D. What is this earlier force, out of which photons and IVBs are thought to have come into a separate existence? This earlier energy state is called the *Higgs field* and its carrier is the *Higgs boson*.
 - 1. The Higgs field and its carrier, if real, are pivotal to the unification of the fundamental forces of nature.
 - 2. The interaction of hadrons with the Higgs field may explain why hadrons have mass. This same line of thinking may also be applied to lepton mass. Mass itself may be an energy interaction with the Higgs field.
 - 3. When the CERN particle accelerator returns to operation in 2006, it should have enough energy (7 Tev) to find the Higgs boson.
- III. The unification of the electro-weak theory and QCD in the 1980s came to be called the *standard model* of matter-energy.
 - A. This framework is the realization of Max Planck's tentative hypothesis, formulated in December 1900, that the absorption and emission of electromagnetic radiation is discrete, not continuous.
 - B. By the end of the century, the idea that natural processes are discrete has flowered into a comprehensive theory of matter and energy that allows us to give satisfying theoretical accounts of the universe, beginning minute fractions of a second after the Big Bang.
- IV. The most exciting prospect for many physicists is the possibility of extending the standard model, which unites QCD and electro-weak theory, to a quantum theory of gravity.
 - A. This would be a theory that unites all four known forces of nature, either by assimilating the general theory of relativity into the standard model or by replacing the general theory of relativity with a better theory of gravity. These attempts at unification are called *supersymmetry theories*.
 - B. Such a unification would identify the original symmetric state of the universe that spontaneously "broke," perhaps only 10^{-43} seconds after the Big Bang, into the gravitational force field and the unified force field underlying the standard model, then broke again and again to form the weak, strong, and electromagnetic forces that determine all "ordinary" phenomena in the universe today.
 - C. In the 1980s–1990s, two supersymmetry theories arose: *string theory* and *loop theory*.
 - 1. It is tempting to wonder if these two "rival" approaches will turn out to be mathematically equivalent, as with wave and matrix mechanics.
 - 2. In both of these theories, the ultimate physical reality is a structure, built of either minute multidimensional loops or multidimensional strings. In both theories, in the instant after the Big Bang, the

universe had 10 dimensions, but these collapsed to 3 dimensions as the universe cooled.

- D.** Another group of theorists has defined a third supersymmetry approach. The distinctive contribution of this approach is the identification of the reality behind gravity and the standard model with process and relationships, not as a “thing” with properties.
1. These theorists draw inspiration from the work of Stephen Hawking and Jakob Bekenstein on the nature of black holes.
 2. Bekenstein, especially, forced a recognition that black holes had complex properties that were properly identified with the concept of *entropy*, defined as a measure of information. Thus, this third group of theorists interprets the universe as an information structure.
 3. Earlier, we acknowledged that energy is “real” and that the universe may “be” energy. Could information be “real” in the same sense? Could the universe “be” information? Is it possible that our universe is a cosmic Burma Shave sign in some far greater scheme of things?

Essential Reading:

Brian Greene, *The Elegant Universe: Superstrings, Hidden Dimensions, and the Quest for the Ultimate Theory*.

Stephen Hawking, *A Brief History of Time*.

Lee Smolin, *Three Roads to Quantum Gravity*.

Supplementary Reading:

Lee Smolin, *The Life of the Cosmos*.

Questions to Consider:

1. How will our thinking about physical reality have to change if, as expected, the Higgs boson is detected at CERN and mass, the most fundamental feature of ordinary experience, is explained away as an effect of the Higgs field?
2. What’s left for physicists to explain if they succeed in formulating a quantum theory of gravity, thus unifying the four forces of nature?
3. Are physicists going too far in postulating that the ultimate structure of the universe, hence all physical reality, is *information*, that is, no *thing* at all?

Lecture Eleven

Chemists Become Designers

Scope: In the course of the 20th century, chemistry has evolved into a more theory-based science, especially mathematics and quantum theory-based, and a science exemplary of cross-disciplinary fertilization. The evolution of chemical bonding theories from 1900 to 2000 includes the triumph of the atomic theory of matter early in the century, the assimilation of quantum theory by chemists in the mid-century, and with access to late-20th-century supercomputers, a growing ability to predict the properties of molecules before they are produced and to produce to order a range of new kinds of “artificial” molecules with properties specified in advance. The implications of this capability are profound for genetic engineering, pharmaceuticals, and the nascent nanotechnology industry, as well as for the manipulation of matter generally in all forms of manufacturing, including the continued miniaturization of sensors and computer components.

Outline

- I. In this lecture, we take a short step away from quantum physics to explore the science of chemistry.
 - A. The essence of chemistry is the study of the way that atoms form molecules and the way that molecules interact with one another. In turn, chemical reactions are determined by the behavior of orbital electrons at the outermost level of the atom.
 - B. Quantum theory is naturally applied to chemistry, then, because it originated in attempts to understand the behavior of orbital electrons.
 - C. Indeed, in the 1930s, Linus Pauling developed a quantum mechanics-based theory of the chemical bond, which became dominant after his 1940 text.
 1. In this theory, Pauling described two kinds of bonds: “weak,” or *ionic* bonds, in which an electron is transferred from one atom to another, and “strong,” or *covalent* bonds, in which an electron is shared between two atoms.
 2. Using quantum theory, Pauling described the conditions in which electrons form ionic and covalent bonds, depending on the energies of the outermost orbital electrons.
- II. Let’s begin by looking at some highlights of chemistry over the course of the 20th century.
 - A. Unlike physics, chemistry in 1900 had very little mathematical theory associated with it.

1. Chemists used thermodynamics to account for energy transfer in chemical reactions. Chemists had also discovered that chemical reactions have a precise quantitative character. These applications of mathematics, however, were relatively modest.
 2. Explanations of molecular structure and chemical reactions were empirical and descriptive.
 3. But chemists could do a great deal with their knowledge that was of practical commercial value, as evidenced by the spin-off in 1900 of chemical engineering from chemistry and strong industry support of chemical research.
- B. Chemistry made a real difference in life.**
1. By 1900, chemistry had created the artificial dye, pharmaceutical, explosives, and cellulose-based synthetics industries.
 2. Soon after 1900, Fritz Haber's synthesis of ammonia from atmospheric nitrogen created the artificial fertilizer industry and eliminated the need for natural saltpeter in the manufacture of explosives.
 3. Bakelite was synthesized in 1907 by Columbia University chemical engineering professor Leo Baekeland, and the plastics industry was born around resin-based materials.
 4. The commercial production of synthetic rubber began in 1910. In 1935, nylon was developed by a DuPont research chemist, and at the same time, the first synthetic drugs, called *sulfa drugs*, were invented by the German chemist Gerhard Domagk. This development played a significant role in shifting Western medicine away from a homeopathic model to allopathic therapies.
- C. A laundry list of the impact of chemistry on 20th-century life can be fascinating, but our focus is on the organizing ideas of the sciences and how they changed from 1900 to 2000. In chemistry, we particularly see the impact of developments and ideas from physics.**
1. One major development in physics that was applied to chemistry was the technique of X-ray crystallography. First proposed in 1912 by Max von Laue, X-ray crystallography, in the 1920s, became a tool for identifying the molecular structure of any substance that could be crystallized. In 1953, X-ray crystallography data revealed the molecular structure of DNA.
 2. A second important tool developed in physics but used in chemistry was the mass spectrometer, which has some similarities to the cyclotron. This device enables chemists to measure molecular weights. Interestingly, the mass spectrometer was invented to prove the existence of isotopes.
 3. Perhaps the most familiar tool for chemists, introduced in the 1940s, was chromatography. This technique allows chemists to identify the constituent molecular groups in complex molecules.

4. The most exciting development may be spectroscopic instruments that allow chemists to “see” chemical reactions at the atomic level in real time. Until the 1960s, chemists could observe reactions on time scales of seconds to, in a few cases, milliseconds. In the 1960s, using lasers, it became possible to observe reactions on the nanosecond level. In the 1980s, *femtosecond* spectroscopy was introduced, which allows chemists to watch reactions on a time scale of 10^{-15} seconds.
- D. Chemists carried many of these techniques into biology, and in the course of the 20th century, biology became increasingly centered on biochemistry. At the same time, biology also assimilated the tools and ideas of physics that had come to be part of chemistry.
1. In 1900, one of the theories that dominated biological thinking was *colloid theory*, which asserted that organic molecules were relatively short but could be linked into weak chains. In 1920, Hermann Staudinger proposed a rival theory of very long, rigid *macromolecules*; Hermann Mark later determined that Staudinger was correct about the existence of macromolecules but mistaken about their rigidity.
 2. The controversy that Staudinger sparked was resolved by the ultracentrifuge, an instrument invented by Theo Svedberg in the late 1920s. The instrument showed that hemoglobin, the first molecule examined, contained 66,000 atoms.
 3. This discovery was pivotal to the growth of polymer chemistry and our understanding of proteins.
- III. All these changes were supported by another family of instruments, beginning in 1931 with the invention of the electron microscope.
- A. The electron microscope was improved between 1931 and 1960 and eventually achieved high resolutions but only in two dimensions. Further, the electron microscope could not image biological materials.
- B. In 1981, the scanning tunneling microscope (STM) was invented, which took advantage of quantum theory. In 1986 and 1987, further development of the STM led to the atomic force microscope, which is capable of imaging a single atom in three dimensions and can image biological materials.
- C. As we close, we return to quantum theory. Computers have now become powerful enough that they can solve the complex quantum mechanical equations associated with multiple atoms sharing electron bonds in complex three-dimensional configurations.
1. By the end of the 20th century, supercomputers were able to model meaningful chemical reactions; thus, quantum chemistry became a subdiscipline that allows calculation of properties of molecules before the molecules are actually created.

2. The implications of this ability to create *designer molecules* for pharmaceuticals and other areas of science and industry are tremendous.

Essential Reading:

Philip Ball, *Designing the Molecular World*.

Trevor Levere, *Transforming Matter: A History of Chemistry from Alchemy to the Buckyball*.

Supplementary Reading:

Mary Jo Nye, *Before Big Science: The Pursuit of Modern Chemistry and Physics, 1800–1940*.

Questions to Consider:

1. Why was chemistry, unlike physics, able to develop into a mature science with very little use of abstract mathematics?
2. Considering that chemists first called attention to the precise spatial organization of atoms as a cause of molecular properties, why was there so much opposition by chemists to precise structure when applied to macromolecules, such as proteins and polymers?
3. Was it scientific for chemists to believe in the reality of the atom for 150 years before the scanning tunneling and atomic force microscopes made atoms visible? Do we actually “see” atoms in these instruments?

Lecture Twelve

Mathematics and Truth

Scope: The general theory of relativity and quantum theory played central roles in the evolution of our conception of the universe between the early 1920s and 2000. But before describing that evolution, it is worth taking some time to appreciate a characteristic of 20th-century science that has been an obstacle to public appreciation of it: the forbidding mathematical language of its theories. The publicity surrounding the “confirmation” of the general theory of relativity made much of the incomprehensibility, even to non-specialist scientists, of this new theory because of its highly abstract mathematics. This was certainly true of the rapidly developing quantum theory, and soon, complex forms of mathematics were essential to the practice of chemistry, biology, psychology, sociology, economics, and even linguistics. Why? What gives mathematics this power? How can mathematical abstractions tell us anything about concrete experience? As we have seen, scientists repeatedly deduce new experiences from mathematical models, which suggests that reality is, in some sense, mathematical.

Outline

- I. This is the first of two lectures on the role of mathematics in the sciences.
 - A. One of the characteristics of science in the 20th century is that it became increasingly mathematical.
 - B. Mathematics is, in a sense, responsible for a disturbing development in the sciences. The practice of science was traditionally open and democratic, but by the late 1800s, physical science had taken on the characteristics of an esoteric cult, because of mathematics.
 - C. This lecture is structured around two ideas: mathematics as the language of science and mathematics as the language of right reasoning.
- II. We begin with mathematics as the language of science.
 - A. Galileo said that nature is, fundamentally, mathematical, so that when you use mathematics in science, you are speaking the language of nature. For this reason, mathematical theories in science are true; they are, in some sense, an image of the underlying structure of reality.
 - B. Even in the 17th century, there was considerable controversy over what role mathematics should play in the sciences. Descartes argued strongly for the use of mathematics as the core of natural science. Francis Bacon, in contrast, was suspicious of mathematics.

- C. This controversy was resolved in favor of mathematics with the work of Newton and Leibniz. In the 19th century, this issue was revived in the question: What is the connection between mathematical models and reality? Some physicists argued that the fact that mathematics makes accurate predictions about nature means that the two are connected. We have seen several examples of this in the history of quantum theory.
- III.** Mathematics also has a long history of association with the notion of right reasoning. The discovery of non-Euclidean geometries in the mid-19th century severed the necessary connection between deductive reasoning and reality. Again, scientists were faced with the question: What is the connection between mathematical truth and physical reality?
- IV.** This question became real for scientists at the end of the 19th century, but it also became an issue for mathematicians. What is the basis of mathematical truth?
- A. In the wake of non-Euclidean geometry, set theory, symbolic logic, and other 19th-century developments, mathematicians experienced a crisis of confidence. Three schools of thought emerged to address the questioning of mathematics: *logicism*, *formalism*, and *intuitionism*.
 - B. At the end of the 19th century, Gottlob Frege embarked on a project to reduce arithmetic to logic.
 - 1. Frege argued that arithmetic and geometry were the “elementary” branches of mathematics from which all others derived, and he attempted to reduce arithmetic to a system of purely logical laws and definitions.
 - 2. Frege’s reduction of arithmetic to logic was revealed by Bertrand Russell to contain a flaw that undermined Frege’s entire project, and Frege abandoned it.
 - 3. Russell, together with Alfred North Whitehead, then attempted an even bolder reduction of *all* of mathematics to logic. This effort, in spite of improvements made by others in the 1920s, is not convincing.
 - 4. Thus, the attempt to reduce mathematics to logic fails. Mathematics is its own branch of knowledge.
 - C. David Hilbert’s formalist interpretation of mathematics made mathematics into a kind of logic game, one in which mathematicians freely invented such terms as *number*, *point*, *line*, *triangle*, *function*, and so on, then explored the logical consequences of these terms in various combinations according to specified rules, for example, addition and multiplication, with these rules also freely invented.
 - 1. For Hilbert, mathematics has no necessary connection at all to anything outside itself and no meaning outside of itself. It is an empirical fact that some mathematical expressions in their logical

structure emulate natural processes and that scientists choose to associate these expressions with “laws” of nature.

2. At a mathematics conference in Paris in 1900, Hilbert challenged the world’s mathematicians to solve a collection of 23 problems that he considered of critical importance. Two of these are of particular interest to us: (a) to show that mathematics is consistent and complete and (b) to show that mathematics includes an effective decision procedure for solving any problem.
 3. In the 1930s, proofs that neither of these can be shown to be true were of profound intellectual and scientific significance.
- D. Finally, an “intuitionist” interpretation of mathematics was championed by Dutch mathematician Luitzen Brouwer. This interpretation is of interest here, because it illustrates that what was at issue early in the 20th century was not mathematics *per se*, but reasoning itself.
1. Brouwer’s view challenged 2400 years of Western intellectual history. He believed that mathematics is an example of the mind imposing order on experience. There is no necessary connection between mathematics and reality.
 2. For Brouwer, mathematical reasoning is fundamentally intuitive. We intuit the kinds of mathematical relationships that will be useful and interesting, then we explore them logically.
 3. The main difference between Brouwer and Hilbert is that Brouwer argued that the *law of contradiction* is not a valid logical law; it is merely an empirical law. A double negative does not necessarily imply a positive. This assertion changes the character of mathematics.

Essential Reading:

John Casti, *Five Golden Rules: Great Theories of 20th-Century Mathematics—and Why They Matter*.

Stuart Shapiro, *Thinking about Mathematics: The Philosophy of Mathematics*.

Benjamin Yandell, *The Honors Class: Hilbert’s Problems and Their Solvers*.

Questions to Consider:

1. Why do we attribute such high value to deductive reasoning when inductive reasoning is the only kind we can apply to ordinary experience?
2. If the basis of truth claims is unclear in mathematics, what should we think of truth claims in science, which is so dependent on the use of mathematics?
3. Which is primary, logic or mathematics? Is truth a matter of logic or of correlation with experience or correspondence with reality?

Timeline

1900	Max Planck's quantum hypothesis. Recovery of Mendel's research on discrete inheritance. David Hilbert's first challenge to the world's mathematicians. Freud's <i>Interpretation of Dreams</i> published.
1903	William Bateson coins term <i>genetics</i> . Marie Curie calculates magnitude of energy released by radium. Fritz Haber announces process for making ammonia from atmospheric nitrogen.
1905	Special theory of relativity. Einstein's photoelectric effect paper founds quantum physics; Brownian motion paper convinces many physicists that atoms are real. Russo-Japanese War: Japan a world power.
1907	Bateson coins term <i>gene</i> . Pareto publishes his theory of society/economy. Creation of Bakelite, launching plastics industry. Emil Fischer shows that proteins are combinations of amino acids.
1908	First nearly complete Neandertal skeleton unearthed.
1909	Gene recombination identified as source of variability for evolution.
1910	T. H. Morgan converted to gene theory by fruit fly research. Rutherford's "solar system" model of atom. Synthetic rubber and rayon.
1912	Bohr's quantum theory of atom. von Laue predicts X-ray crystallography.

1913	Charles Beard's <i>Economic Interpretation of the U.S. Constitution</i> . Henrietta Leavitt announces cosmic "yardstick." First absolute geological time scale. John Watson founds behavioral psychology.
1914	World War I; German intellectuals publish "Declaration to the Civilized World."
1915	General theory of relativity. Wegener's continental drift theory.
1916	Ferdinand de Saussure's "Course in General Linguistics" published posthumously by his students. Harlow Shapley announces first cosmic distance: 400,000 light years to Large Magellanic Cloud.
1918	World War I ends.
1919	Confirmation of general theory of relativity's prediction of bending of light rays. Mt. Wilson Observatory 100-inch telescope becomes operational observatory.
1920	Harlow Shapley defends Milky Way as only galaxy in public debate.
1923	Louis de Broglie predicts matter waves if the special theory of relativity and quantum theory are correct. <i>Scopes</i> trial in Tennessee ends in conviction.
1924	Edwin Hubble announces Andromeda "nebula" is a galaxy, and thousands more galaxies are out there.
1925	Erwin Schrödinger and Werner Heisenberg create quantum mechanics.
1927	Heisenberg's uncertainty principle. First artificial mutations induced by radiation.

1929	Hubble announces expanding universe. Copenhagen interpretation of quantum mechanics. Dirac combines the special theory of relativity and quantum mechanics, leading to the creation of quantum electrodynamics. New York Stock Exchange crash; global depression begins.
1930	Dirac predicts existence of anti-electron/positron. Pauli predicts existence of neutrino to explain beta decay. Population genetics theory formalized, reviving Darwinism.
1931	Cockcroft and Walton achieve first artificial transmutation of one element into another. Lawrence team builds first cyclotron. Gödel's proof published. Electron microscope invented.
1932	Carl Anderson discovers Dirac's positron. James Chadwick discovers neutron. Blackett and Occhialini confirm energy can become matter.
1935	Sulfonamide drugs invented. Nylon invented. Radiotelescopy invented by Karl Jansky.
1936	J. M. Keynes publishes his <i>General Theory</i> . Quantum theory of nucleus founds nuclear physics. Nuclear fission research frenzy. Turing's proof; conceptual design of computer.
1938	Bethe's fusion theory of stellar energy. B. F. Skinner revives behaviorism against Gestalt psychology, psychoanalysis.
1939	Fission of uranium with great energy release announced. Gamow's initial Big Bang hypothesis. World War II begins.
1940	Vannevar Bush convinces Roosevelt to create the National Defense Research

	Council, which becomes the Organization for Scientific Research and Development when the United States declares war. Linus Pauling's chemical bond theory published.
1942	Manhattan Project created. Enrico Fermi-led team builds first nuclear reactor. First of 10 annual Josiah Macy Foundation conferences. McCulloch and Pitts propose electrical model of neurons.
1943	Game theory introduced.
1944	Oswald Avery shows DNA basis of heredity. Turing publishes <i>Machine Intelligence</i> .
1945	Germany surrenders (May). "Trinity" A-bomb test, Alamogordo, New Mexico (July). Hiroshima and Nagasaki A-bombs (Aug.). Japan surrenders (Aug.). ENIAC becomes operational.
1946	QED problems resolved by Schwinger, Feynman, Tomonaga.
1947	Radiocarbon 14 dating method invented by Willard Libby. Complete molecular structure of insulin determined.
1948	Invention of transistor. Norbert Wiener's <i>Cybernetics</i> published. Shannon/Weaver information/communication theory. Hoyle-Bondi-Gold propose the Steady State theory of the universe.
1949	EDVAC, first stored-program electronic computer. Wiener predicts microwave background radiation. Palomar 200-inch telescope becomes operational.
1950	National Science Foundation created.

1951	Invention of maser. Pauling determines helical structure of protein molecules.
1952	Twenty European nations form joint Center for European Nuclear Research.
1953	Watson and Crick announce double-helix structure of DNA.
1954	Berkeley Bevatron reaches 6.2-GeV energy, discovers anti-proton.
1956	First artificial intelligence conference.
1957	Sputniks 1 and 2 orbit Earth. Mechanism of DNA replication revealed. Noam Chomsky's <i>Syntactic Structures</i> published.
1958	First U.S. satellites; discovery of Van Allen radiation belts. Quasars detected.
1959	First neural net computer, Perceptron.
1960	Invention of laser. Transit, Tiros, Echostar orbital satellites. President Eisenhower warns of military-industrial complex.
1962	Gell-Mann and Ne'eman's Eightfold Way classification of elementary particles. Penzias and Wilson detect microwave background radiation. Rachel Carson's <i>Silent Spring</i> published. Thomas Kuhn's <i>The Structure of Scientific Revolutions</i> .
1963	MIT AI lab founded.
1964	Gell-Mann and Zweig announce three-quark theory of matter, founding QCD.
1966	Tanzania's Olduvai Gorge excavations reveal antiquity of human lineage and culture.
1967	The United States creates FermiLab national particle accelerator research center.

	First chess-playing program.
1968	Plate tectonics theory becomes mainstream geology.
1969	First Apollo moon landing. Environmental Protection Agency created. Clean Air and Water Acts passed.
1970	First black hole candidate detected, Cygnus X-1.
1971	Electro-weak theory proposed.
1972	First Landsat satellite orbited. First recombinant DNA experiment First commercial CAT-scanning machine.
1973	Fourth quark discovered by B. Richter and by S. Ting. Mariner space probe to Mercury.
1974	“Lucy” skeleton unearthed in east Africa, crystallizing the out-of-Africa hypothesis of human origins.
1976	Viking probes land on Mars.
1977	Fifth quark discovered by Leon Lederman. Voyager 1 and 2 space probes launched to outer planets. Mid-ocean thermal vents discovered.
1978	Pioneer space probe to Venus.
1979	Luis Alvarez proposes collision theory of dinosaur extinction.
1980	Alan Guth proposes cosmological inflation theory.
1981	Scanning tunneling microscope invented, atoms imaged. First commercial MRI machine.
1982	FDA approves recombinant DNA insulin from bacteria.
1983	Electro-weak theory confirmed by discovery of predicted intermediate vector bosons. First monoclonal antibody approved by FDA.

1985	PCR method for mass replication of DNA invented. Recombinant Human Growth Hormone approved.
1988	Atomic force microscope invented: three-dimensional atomic images.
1989	Human Genome Project announced.
1990	Hubble Space Telescope orbited.
1991	<i>Homo erectus</i> bones found in Republic of Georgia.
1994	U.S. Congress cancels Superconducting SuperCollider.
1995	Sixth quark discovered.
1997	Deep Blue chess computer defeats Gary Kasparov.
1998	Acceleration of universe's expansion announced.
2000	Keck telescope observes transit of planet 153 light years away. Human Genome Project successfully completed.
2002	NASA LIGO gravity wave telescope operational.
2003	NASA Space Infra-Red Telescope Facility orbited.

Glossary

Aether: The name given by 19th-century physicists to a cosmic space-filling substance that served as the medium in which light waves traveled. The special theory of relativity and the quantum theory made the aether unnecessary.

Amino acids: The building blocks of proteins, amino acids are organic molecules that can form short or long chains, called *peptides* and *polypeptides*, respectively.

Angiogram: X-ray photographs of blood vessels, whose soft tissue is ordinarily transparent to X-rays, made by injecting a substance opaque to radiation.

Atomic number: The number of protons in the nucleus of an atom, unique to each element.

Atomic weight: The total number of protons plus neutrons in the nucleus of an atom.

ATP: Adenosine triphosphate, a protein that is the key source of chemical energy in all organisms.

Aurignacean: The name given by archaeologists to the forms of culture exhibited by early humans, predominantly Neandertals, from about 400,000 B.C.E. to 50,000 B.C.E.

Autocatalytic: In chemistry, a reaction caused by the products of a catalytic reaction but also applied to self-organizing and complex systems in which nonequilibrium is sustained by the products of the systems' own activity.

Baryon: Particles that respond to the strong force, contained in the nuclei of atoms; thus, in the standard model, all of the particles composed of combinations of three quarks held together by gluons, especially protons and neutrons.

Biologicals: Biologically based products that provide immunity to disease.

Blackbody: A term used by physicists to describe an object that absorbs all of the electromagnetic radiation, of whatever frequency, that is incident upon it.

Brownian motion: The erratic, random motion displayed by minute particles suspended in a fluid, the cause being the random motions of the atoms or molecules in the fluid.

Bubble chamber: An instrument invented by Donald Glaser in 1952 for revealing visual evidence of high-energy "elementary" particles created in particle accelerator collisions.

Buckyballs: Colloquial for buckminsterfullerene, a roughly soccer ball-shaped molecule of 60 carbon atoms first created in 1985 and useful for

storing/transporting molecules that can be trapped and released in a controlled fashion.

Carbon nanotubes: The process that produces buckyballs can also produce cylindrical carbon atom tubes, each of nanometer length (10^{-9} meters) that can be concatenated into much longer cylinders of enormous strength.

Carrier (of force): In quantum theory, every force is “carried” by a particle whose exchange is the exertion of the force. For example, the electromagnetic force is carried by photons and acts when a photon is absorbed or emitted.

Chaos theory: The colorful but somewhat misleading name given to complex but deterministic physical systems, such as the atmosphere, that are nonlinear, that is, in which minute changes in input lead to large changes in behavior.

Chromatography: A now-universal technique developed in the 1940s and after for separating the molecules in a compound by their molecular weight. The technique exploits the selective adsorption (surface adhesion) of molecules in either gas or liquid form onto a solid material, for example, specially treated paper.

Cloud chamber: An instrument that uses supersaturated water vapor to visualize charged particles that cause ionization trails to form when they pass through the chamber.

Commutativity: The rule in mathematics that the sequence of an operation is irrelevant. Thus, addition and multiplication are commutative, because $n + m = m + n$ and $n \times m = m \times n$, but subtraction and division are non-commutative because the order of operation makes a difference.

Completeness: In logic and mathematics, the property that an axiomatic system will generate all of the theorems that are true in that system.

Complexity theory: See **chaos theory**.

Conservation of energy: The principle, fundamental to classical thermodynamics, that energy can neither be created nor destroyed, only transformed from one form into another, for example, from motion into heat.

Conservation of matter: The principle that matter can neither be created nor destroyed and, thus, that the total amount of matter in the universe is constant. After the special theory of relativity and quantum theory, matter can be created out of energy and converted into energy, so it is the total of matter-energy that is conserved, not each separately.

Consistency: In logic and mathematics, the property of an axiomatic system that is free of contradiction.

Correspondence principle: Formulated by Niels Bohr in 1919, it states that there are fertile correspondences between classical and quantum physics in spite

of their exclusivity, because as quantum systems increase in complexity, they become classical systems.

Creationism: The view, opposing Darwinism, that the universe, and especially the Earth and man, were created by a Providential Deity.

Cybernetics: The name given by Norbert Wiener to the theory of machines, organisms, and information systems that display apparently purposive behavior by exploiting feedback and self-regulatory control circuits.

Deconstruction: The theory, initially applied in the 1960s and 1970s to literary works but then more widely, that meaning was, in principle, indeterminate, because it is a function of open-ended relationships involving the entire cultural network in which interpretation takes place.

Deduction: A form of logical argument in which the conclusion must be true if the premises are.

Diachronic: Historical; change over time.

Differential geometry: A form of geometry in which spatial relationships, for example, the properties of curves, are described in general terms and studied using the differential calculus.

Diffraction: When examined closely, the shadow cast by a light beam is not sharp and, in fact, displays interference patterns, as if the beam were a wave wrapping around the opaque edge casting the shadow.

Dynamics: A system in which unbalanced forces are acting, thus, not in equilibrium.

Dynamo effect: Moving a magnet around a conductor, or moving a conductor around a magnet, causes a current to flow in the conductor. This remains the principle underlying virtually all electricity generation today (except for photovoltaic and thermoelectric generation).

Electromagnetic theory: Maxwell's theory of the 1860s according to which electricity and magnetism or moving charged particles can interact to generate waves of energy that, in a vacuum, travel at the speed of light, visible light being those waves to whose frequencies our eyes are sensitive.

Electron beam diffraction: The diffraction of a beam of electrons (or even of atoms) analogous to the diffraction of beams of light. Predicted by Louis de Broglie in 1923, it revealed that particles behaved like waves by displaying interference effects.

Emergence: Colloquially, what people mean by the whole being greater than the sum of its parts, that is, systems/wholes can display properties that are not displayed by any of the parts of which the system/whole is composed.

Encephalography: Studying the structure and activity of the brain, by X-ray photography, displacing the cerebrospinal fluid by air to serve as a contrast medium; electrically, using electroencephalography, or EEG; or acoustically, using ultrasound.

Entropy: In thermodynamics, a measure of the *unavailability* of energy in a closed system, reflecting the irreversibility of real-world processes and, in 19th-century physics, implying the ultimate running down, or “heat death,” of the universe. The study of self-organizing systems in the second half of the 20th century led to a reinterpretation of entropy.

Enzymes: Proteins that serve as catalysts in reactions; that is, they are not themselves changed by the reaction.

Equilibrium: A system in which no unbalanced forces are operating and with no cumulative, directed changes taking place is in equilibrium.

Ethical drugs: Synthesized pharmaceuticals, a late-19th-century spin-off of the invention of synthetic dyes beginning in 1856.

Eukaryote: Cells with a nucleus separated from the rest of the cell by a membrane.

Field theory: The mid-19th-century theory, championed especially by Michael Faraday and James Clerk Maxwell, that certain forces, among them, electrical and magnetic repulsion and attraction, acted not by direct mechanical contact between sources, but at a distance, by filling the space surrounding the source of the field in accordance with precise mathematical laws.

Fractal geometry: The name given by Benoit Mandelbrot to the fractional dimensionality of self-similar shapes.

Functionalism: Any theory whose objective is determining how the elements of a system function and what their mutual interrelationships are; rather than determining what they “are” ultimately or what they mean, just what they do.

Game theory: In von Neumann and Morgenstern’s 1943 classic text, the theory of choices made by participants in a conflict situation, assuming that each attempts to maximize his or her self-interest, hence, the basis of rational choice theory. Later, game theory was extended to cooperative game situations. Very widely applied in economics and social science.

Geisteswissenschaft: A German word invented in the late 19th century to denote knowledge of human social and cultural phenomena, acquired through objective, critical, methodological study; thus, what we now call the humanities and social sciences.

Geodetics: Mapping the Earth’s surface with special attention to elevation and deviation from sphericity, hence, requiring measurement of variation in the gravitational force.

Group theory: A branch of mathematics that studies the properties of sets under some rules for operating on them (addition, multiplication, and so on).

Hadron: A generic name for the families of strong force–interacting (hence, nuclear) particles that, according to quantum chromodynamics, make up all ordinary matter. Hadrons are either baryons or mesons, composed of quark-anti-quark pairs. Leptons are the other family of elementary particles, responding to the weak force. Leptons and hadrons are connected by the beta decay process that neutrons and mesons exhibit. *Hadron* is sometimes used to refer to both weak and strong force–responsive particles.

Hydrothermal vents: Fault lines in the ocean floor, typically near the mid-ocean ridges, from which hot, mineral-rich water pours, the water heated by contact with molten rock beneath the ocean floor, and surrounded by flourishing dense ecologies of plants and animals, even at temperatures above the boiling point of water.

Induction: A form of inference in which the conclusion reached may be false even if the premises are all true, hence, probabilistic inference, as opposed to deductive inference, in which the conclusion must be true if the premises are true.

Information theory: Especially after Claude Shannon’s 1948 formulation, the mathematical study of the character, storage, and transfer of information using probability theory and interpreting information as the opposite of the thermodynamic concept of entropy (hence, *negentropy*, a term coined by Norbert Wiener).

Interference: A name for interactions among overlapping waves which, depending on the timing and form of their overlap, can cancel each other out, reinforce one another to form a single stronger wave, or form some more complex hybrid wave.

Interferometry: A technique in which a beam of light is divided in two and, after traveling separate, carefully controlled paths, the two beams are caused to overlap, for example, by reflecting mirrors. The resulting interference patterns allow extremely accurate measurement of the wavelength of the waves and/or of the distances the beams have traveled. Interferometry is fundamental to late-20th-century radio, visible light, and gravity wave telescopes.

Interferon: A protein produced by cells in response to viral infection.

Interstellar wind: The flow of atoms and molecules across interstellar space, typically produced by nova and supernova.

Isostasy: A turn-of-the-20th-century American geological theory that explained the equilibrium of the Earth’s surface, deformed by mountains and valleys, by postulating a constant net density and uniform net gravitational force. Thus, the “excess” of matter associated with mountains is compensated for by assuming that the matter beneath the mountains was less dense than average.

Kuiper Belt: A vast region of the solar system beginning just beyond Neptune and extending far beyond the orbit of Pluto. It is believed to contain hundreds of thousands of comet nuclei and *planetesimals* (“micro-planets”) and to be the source of those comets that return periodically. Pluto may be a Kuiper Belt object rather than a “true” planet.

Lepton: In quantum chromodynamics, the family of elementary particles made up of electrons, pions, and tau particles and their respective neutrinos. Leptons respond to the so-called weak force and to the electromagnetic force but not to the strong force.

Magnetic moment: A measure of the strength of a magnet. In quantum theory, charged particles, such as the electron, and nuclei as wholes have magnetic moments and, thus, magnet-like properties that can be exploited to manipulate matter in subtle ways.

Metabolomics: The study of the correlation between proteins and metabolic processes, without first understanding how the structure of a protein determines its action.

Mitochondria: A cellular structure with its own membranes and its own short ring of DNA, outside the nucleus, in which ATP is produced. Except for random mutations, it is believed that mitochondrial DNA rings are transmitted from mother to daughter identically and, thus, can serve as an absolute genealogical marker.

Modernity: A name for the commitment to reason, especially as exemplified in natural science, mathematics, and logic, as the only means by which truth, knowledge, and progressive improvement of the human condition can be achieved.

Monoclonal antibody: An antibody produced by a cell culture created by cloning a single parent cell, so that the antibody produced by all the cells in the culture is identical.

Mousterian: A name for the more sophisticated culture—tools, artifacts, art, and lifestyle—of *Homo sapiens* and, possibly, Neandertals in the period 50,000–30,000 B.C.E.

Mutation: In genetics, a random change in the base sequences in the DNA molecule, thereby affecting the gene coding for protein synthesis and, ultimately, the cellular process(es) the protein participated in. Sometimes, chromosomes undergo random structural changes that are also called mutations.

Nanotechnology: Technologies based on the manipulation of matter at the level of 10^{-9} meters, typically, on the order of tens to a few hundreds of atoms in size.

Naturwissenschaft: Scientific knowledge of natural phenomena.

Network theory: A branch of mathematics that studies the properties of networks that emerge as a result of their structure, that is, of the form of the connections among the network's nodes.

Neural nets (or networks): A type of computer inspired by the neuronal structure of the brain. The computing in a neural net computer does not follow a rigorously controlled sequence of program instructions. Instead, the input nodes of the net are linked to output nodes by one or more layers of intermediate nodes, all interconnected and with the intermediate nodes free to set their own responses to inputs and feedback from outputs. Neural nets are not programmed in the traditional sense; they are "trained" to adjust themselves internally to reliably generate a desired output for a given input.

Neutron star: A collapsed star too small to form a black hole.

Newtonian science: The search for experimentally validated mathematical laws for the motion of matter under the action of specified forces. More specifically, physics keyed to Newton's definitions of space, time, and matter and Newton's laws of motion. Broadly, modern science from Newton to Einstein.

NMR: Nuclear magnetic resonance, the basis of magnetic resonance imaging (MRI) technology. A nucleus with a magnetic moment behaves like a magnet and, in a strong magnetic field, if stimulated by radio waves of appropriate frequency, will radiate a signal that can be used to create an image of the sample nuclei.

Nonequilibrium state: A condition of directed change, produced by the action of forces in a system.

Non-Euclidean geometry: Any logically valid, deductive system of geometry that uses definitions, axioms, or postulates different from the ones used by Euclid.

Nonlinear system: One in which small changes in input or initial conditions result in large changes in output over time.

Oncogene: A gene linked to cancer because it causes uncontrolled cell growth.

Organic: In chemistry, carbon molecule-based reactions and, by extension, reactions associated with biological molecules.

Particle theory of light: Any theory that light is composed of particles, not waves. This explains the linear transmission and reflection of light beams, the apparent sharpness of shadows, and in the 20th century, many quantum-level phenomena, such as the photoelectric effect, but not refraction, diffraction, or interference.

Perceptron: The first neural net computer, a primitive single-layer device built by Frank Rosenblatt around 1960.

Periodic table: Dmitri Mendeleev's late-1860s innovative organization of the chemical elements based on their chemical weights and "family" chemical properties.

Photoelectric effect: The emission of electrons by certain materials, typically metals and semiconductors.

Pitldown Man: An elaborate and extraordinarily successful fraud that misled paleoanthropologists for decades. A fossil human-like skull unearthed in 1912 near Pitldown in the county of Sussex in England was hailed as the missing link between apes and man because it had an ape-like jaw and a human cranium. Radiocarbon dating techniques in 1953 revealed the skull to be a fraud.

Plate tectonics: The theory that the Earth's surface/crust is in constant motion as a result of the continual upwelling of molten material from the mantle at mid-ocean ridges. This upwelling, driven by convection currents in the mantle carrying away the great heat of the Earth's iron core, forces the ocean floor to spread and, where the floor collides with the continental "plates," to descend into the mantle to melt again. The pressure of the spreading floor keeps the plates in continual motion as well, and when they collide, mountains form.

Positron: An anti-electron, that is, a particle with exactly the same physical properties as an electron but with a positive charge.

Prokaryotes: Cells without a nucleus.

Proteins: The complex molecules, composed of combinations of amino acids, that control cell metabolism. There are some 10,000 different proteins in the human body, out of the millions of possible combinations of amino acids.

Proteomics: The study of the complex, folded shapes and functions of individual proteins, especially the relationship between shape and function.

Pulsars: Rapidly rotating magnetized neutron stars that, like cosmic lighthouses, emit beams of electromagnetic radiation as they spin.

Quantum mechanics: A name applied by Max Born to the successful quantized theories of matter and energy presented by Schrödinger and Heisenberg in 1925. Subsequently, used generically for quantum physical theories, such as quantum electrodynamics and quantum chromodynamics.

Radiogenic heat: Heat whose source is the decay of radioactive elements. The discovery of radioactivity in 1896 quickly led geologists to realize that changes in the Earth's surface could be driven by a continuing source of energy.

Rational choice theory: See **game theory**.

Recombinant DNA technology: Using special enzymes to cut and paste segments of DNA from different individuals of the same type or different types of organisms.

Resonance: When a system of any kind is stimulated, even at very low power at its natural frequency of vibration, very large increases in the energy of the system can be achieved.

Science Wars: A name for the “battle” in the 1980s and after between those who argued that objective knowledge is not possible because all knowledge is necessarily interpretive and, thus, value-laden and those who defended science, at least, as providing objective knowledge of an independently existing reality.

Self-organization: Many kinds of physical, chemical, and biological systems exhibit and sustain spontaneous order under specifiable conditions. Such systems must be thermodynamically open, that is, capable of drawing energy from their environment, and thus, the classical limitations of entropy do not apply to them, but they exist as subsystems within a wider closed system.

Set theory: The study of the properties of collections of objects depending on the axioms imposed on membership in the set and relationships among sets. Set theory became central to attempts to understand the foundations of mathematical truth in the late 19th and early 20th centuries.

Solar wind: The charged particles—electrons, protons, nuclei—blown outward by the dynamic processes at work in the Sun: flares, coronal storms, prominences. There are high-speed and low-speed winds, and during particularly violent storms, perhaps associated with the 11-year sunspot cycle, they pose serious threats to electronics on the Earth and in orbit.

Spectroscopy: The study of the distinct frequencies, wavelengths, and energies of which emitted and absorbed light (and electromagnetic energy generally) is composed.

Spin: A quantum property assigned to charged particles (photons have zero spin) as if they were little tops and could spin clockwise or counterclockwise, thus having one of two possible values characteristic of that type of particle. It is the spin that generates the magnetic moment associated with a particle and, thus, its magnet-like behavior.

Symbolic logic: One name for modern logic, which uses symbolic notation to study much more complex forms of reasoning/inference than in traditional Aristotelian logic. The use of symbols, pioneered by George Boole and extended by Gottlob Frege to a mathematization of logic, stimulated the identification of new logical concepts and the exploration of the properties belonging to relationships other than the classical subject-predicate relationship.

Synchronic: Contemporary; at the same time.

Systems theory: The study of the nature of part-whole relationships and the emergent properties of specific systems; a central concern of researchers studying complexity theory and self-organization.

Tectonics: The surface deformations of the Earth.

Thermodynamics: The study of the laws governing the behavior of heat.

Tomography: A mathematical technique for reconstructing a three-dimensional image of an object (the Earth's interior, the brain, and so on) from sequential two-dimensional sections of that object.

Topology: That branch of mathematics that studies spatial relationships under various imposed restrictions in the most general terms. Also applied to the properties of network relationships and, metaphorically, to relationships in general.

Transgenic: Using recombinant DNA technology to transfer genetic material across species.

Transistor: Exploiting the junction properties of semiconductor materials to accomplish the same electrical circuit functions as vacuum tubes—rectification of current, amplification, detection, switching—at much smaller sizes and with much lower energy requirements.

Wave theory of light: In the 19th century, the theory that light was a wave, not a particle, and furthermore, a transverse wave, that is, one whose wave pattern was at right angles to the direction of travel. In the 1860s, Maxwell argued that light was a product of conjoined electrical and magnetic waves and Einstein, in 1905, postulated that the speed of light in a vacuum was a constant for all observers in uniform motion.

Wissenschaft: Knowledge acquired through the application of an objective, critical methodology, thus, scholarly or scientific knowledge.

X-ray crystallography: Using diffraction to determine the structure of a specimen crystal. A beam of X-rays is focused on the crystal and the diffraction pattern (see **diffraction**) created by the edges of the crystal reveals the angles at which the atoms composing the crystal are arranged. The structure of any substance that can be crystallized can be determined in this way.

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Part II
Professor Steven L. Goldman**



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Steven Goldman has degrees in physics (B.Sc., Polytechnic University of New York) and philosophy (M.A., Ph.D., Boston University) and, since 1977, has been the Andrew W. Mellon Distinguished Professor in the Humanities at Lehigh University. He has a joint appointment in the departments of philosophy and history because his teaching and research focus on the history, philosophy, and social relations of modern science and technology. Professor Goldman came to Lehigh from the philosophy department at the State College campus of Pennsylvania State University, where he was a co-founder of one of the first U.S. academic programs in science, technology, and society (STS) studies. For 11 years (1977–1988), he served as director of Lehigh's STS program and was a co-founder of the National Association of Science, Technology and Society Studies. Professor Goldman has received the Lindback Distinguished Teaching Award from Lehigh University and a Book-of-the-Year Award for a book he co-authored (another book was a finalist and translated into 10 languages). He has been a national lecturer for Sigma Xi—the scientific research society—and a national program consultant for the National Endowment for the Humanities. He has served as a board member or as editor/advisory editor for a number of professional organizations and journals and was a co-founder of Lehigh University Press and, for many years, co-editor of its Research in Technology Studies series.

Since the early 1960s, Professor Goldman has studied the historical development of the conceptual framework of modern science in relation to its Western cultural context, tracing its emergence from medieval and Renaissance approaches to the study of nature through its transformation in the 20th century. He has published numerous scholarly articles on his social-historical approach to medieval and Renaissance nature philosophy and to modern science from the 17th to the 20th centuries and has lectured on these subjects at conferences and universities across the United States, in Europe, and in Asia. In the late 1970s, the professor began a similar social-historical study of technology and technological innovation since the Industrial Revolution. In the 1980s, he published a series of articles on innovation as a socially driven process and on the role played in that process by the knowledge created by scientists and engineers. These articles led to participation in science and technology policy initiatives of the federal government, which in turn, led to extensive research and numerous article and book publications through the 1990s on emerging synergies that were transforming relationships among knowledge, innovation, and global commerce.

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Science in the Twentieth Century: A Social-Intellectual Survey

Scope:

In the course of the 20th century, the practice of science, professionally, intellectually, and in relation to society, increased in scope, scale, and complexity far beyond what had been anticipated at the end of the 19th century. All of the sciences became inextricably entangled with social, political, and commercial forces and values. From the perspective of society, at least, this erased the distinction between pure and applied science, between knowledge and its “fruits,” which had been passionately espoused by many leading 19th-century scientists. As scientists created increasingly powerful theories, people—often scientists themselves—applied those theories to develop technologies whose exploitation created new wealth, new forms of power and control, new ways of life...and new dependencies on more science to create newer technologies!

Concurrently, the practice of science became increasingly formalized, institutionalized, and professionalized. This professionalization reflected and was driven both by the rise of a large number of people who made a living as scientists, in comparison with the comparatively modest community of mostly gentlemen scientists in the 19th century, and by the steadily increasing significance of science to society from the last third of the 19th century through the 20th century. Two hundred and fifty years after the pioneering work of Descartes, Francis Bacon, and Galileo, science suddenly mattered—not just to intellectuals, but to everyone and in profoundly existential ways.

Intellectually, too, the discoveries and theories of 20th-century physical, life, and social scientists exceeded anything that had been anticipated, even by the greatest of 19th-century scientists. As 1900 approached, leading physicists claimed that, apart from the details, the task of science was nearing completion; however, by the end of the 20th century, effectively every 19th-century theory of natural and social phenomena would be overthrown or superseded.

The first lecture in this course establishes its objective: to trace an intellectual history of the physical, life, and social sciences in the 20th century, organized around an evolving scientific understanding of matter and energy, the universe, Earth, life, and humanity, subsuming under the last category theories of culture, society, and mind.

Complementing this survey of a century of science from the “inside,” in terms of its ideas and discoveries, will be an account of the evolution of 20th-century science from the “outside,” that is, of its evolving relationship with society. It is this reciprocal relationship between science and society that makes an understanding of the sciences as a whole in the 20th century important, and not

simply as history, because science is implicated in all of our 21st-century prospects, the threats no less than the promises.

Lectures Two through Eleven describe our evolving understanding of matter and energy, the foundations of the physical and life sciences. We begin with the special and general theories of relativity and how they redefined what we mean by space, time, matter, energy, and motion: in short, what the framework of reality is for the physical sciences.

Given that quantum theory is the most important and intellectually revolutionary scientific theory of the 20th century, eight lectures are devoted to it. Lectures Three and Four trace the early history of the theory, from the tentative introduction of the quantum hypothesis in 1900 to the formulation of quantum mechanics in 1925 and its radical Copenhagen interpretation in 1929. Our goal is a qualitative appreciation of the innovative ideas underlying the theory and of the bizarre microworld underlying ordinary experience that it revealed. Lectures Five through Eight describe the creation and application of the second stage of quantum theory's development, quantum electrodynamics (QED), from 1929 to 1965. Lectures Nine and Ten describe the transition from QED to quantum chromodynamics (QCD) and the unification of all known fundamental forces of nature.

Lecture Eleven concludes the discussion of matter and energy by highlighting major events in the evolution of chemistry, emphasizing the transformation wrought by its assimilation of quantum theory and its growing power to create molecules by design.

The obscurity of the theories of 20th-century physical science from the perspective of the non-scientist public is overwhelmingly a consequence of the forbidding mathematics that has become the language of science. Lectures Twelve and Thirteen discuss controversies in the first half of the 20th century over the relationship between mathematics and truth, and between mathematics and reality, as well as the astonishing fertility of abstract mathematics for the sciences, even if the source of that fertility is not understood.

What we mean by the *universe* has changed, from 1900 to 2000, far more dramatically than anything else in the history of science, more even than the change wrought by Copernicus. Today, the universe is unimaginably more vast than it was thought to be in 1900, and the stories of its origin, constitution, and fate, discussed in Lectures Fourteen through Sixteen, are beyond science fiction!

Lectures Seventeen through Nineteen focus on our knowledge of planet Earth, especially the shift from a geology of static continents to plate tectonic theory. We also discuss the growing recognition of the Earth as a complex system, integrating a dynamic, evolving, physical Earth with its biosphere, oceans, atmosphere, and external and internal magnetic fields, the whole interacting with the solar system in general and the Sun in particular.

Lectures Twenty and Twenty-One address the “outside” of science, especially the rise of techno-science (science-based technology) and its connections to government, industry, and society.

Lectures Twenty-Two through Twenty-Six address our understanding of life, treating the history of evolutionary biology, human evolution, genetics, molecular biology, and science-based medicine.

Lectures Twenty-Seven through Thirty-Four focus on our knowledge of humanity. This group includes three lectures on the evolution of anthropological theories of human culture, the field and theoretical work of archaeologists, important developments in linguistic theory, and changing conceptions of history as a science. Three lectures describe theories of society, the state, and economies, theories that have had profound implications for national and global political agendas and actions in the course of the 20th century. Two lectures describe changing theories of the human mind, our most intimate attempt at self-understanding, from the enormously influential theories of the unconscious by Freud and Jung early in the century, through the equally influential behavioral psychology that dominated the mid-century, to the cognitive psychology that came to the fore in the late century, especially cognitive neuroscience allied to artificial intelligence research.

Lectures Thirty-Five and Thirty-Six review the major concepts of 20th-century science and discuss their broader cultural and intellectual significance, survey the leading edges of the sciences at the close of the 20th century, and look ahead to the continuing evolution of science in the 21st century.

Lecture Thirteen

Mathematics and Reality

Scope: Although more difficult to communicate qualitatively, the development of mathematics in the 20th century was every bit as breathtaking as the development of theories of matter, energy, life, the Earth, and the universe. David Hilbert's challenge to mathematicians was highly technical and esoteric, but it provoked surprising consequences. Kurt Gödel's 1931 proof that the logical consistency and completeness of mathematics could not be proven was a philosophical bombshell on a par with Heisenberg's uncertainty principle, announced five years earlier. Five years later, in 1936, Alan Turing's extension of Gödel's work proved that no rule-based procedure, or algorithm, could exist, even in principle, that would guarantee a solution to every mathematical problem, though Hilbert's formalist interpretation of mathematics required that it should. The means by which Turing established this led directly to the theory of computing and underlies modern computer science. At the same time, developments in mathematics during and after World War II led to game theory, cybernetics and information theory, network theory, fractal geometry, chaos theory, systems and complexity theories, and the discovery of self-organization.

Outline

- I. Regardless of the confusion among mathematicians in the early 20th century, mathematicians continued to generate new mathematical knowledge at an astonishing rate.
 - A. In general, it is fair to say that mathematicians live with a peculiar, unresolved problem: What is the nature of mathematical objects? Do they exist independently of the human mind or not?
 - B. Most mathematicians will privately assert that mathematical objects do exist independently of the mind. That is to say, we *discovered* the triangle and its properties; we didn't *invent* them. But if that is the case, how do we learn about mathematical objects?
- II. In 1931, Kurt Gödel demonstrated that the consistency and completeness of any axiomatic system as simple as ordinary arithmetic could not be proven.
 - A. Using tools of mathematical logic developed by Frege, Russell, and others earlier in the century, together with a technique derived from the set theory of George Cantor, Gödel created an ingenious proof that any axiomatic system necessarily generated statements that could not be proven to be either true or false within that system.

- B. Gödel's proof was a major event in the 2500-year-long history of mathematics in Western culture, on a par with the shock caused by non-Euclidean geometries. The proof showed that the formalist interpretation of mathematics was not possible, as the logicist wasn't. Most mathematicians do not believe that intuitionism is correct either, so we are left with the question: What is the nature of mathematical truth?
 - C. In 1936, Alan Turing built on Gödel's proof to solve David Hilbert's problem of the effective procedure. Turing proved that no effective decision procedure existed for solving all problems in arithmetic.
 - 1. Turing constructed his proof around an imaginary machine, now called a *Turing machine*, that acted on itself in accordance with a fixed set of instructions built into it.
 - 2. This simple conceptual machine allowed Turing to solve the negative of Hilbert's problem. Turing also recognized that a corollary of his proof was that such a machine could solve any logical or mathematical problem for which an algorithm *could* be specified.
 - 3. Turing was unaware, in 1936, that his theoretical work paralleled work in the United States that reached the same conclusions he had and that World War II would make his imaginary machines real, leading in 1949 to the first electronic, stored-program digital computer.
 - 4. During the war, Turing used a kind of analog computer to break the Enigma Code. After the war, he worked on the first generation of electronic, stored-program digital computers in England. Turing was found dead under mysterious circumstances shortly after his conviction for homosexuality in the late 1950s.
- III. We will focus on two aspects of the use of computing that are particularly interesting for science and mathematics: the use of computer simulations in science and the use of computer capabilities in mathematical proofs.
- A. Computer simulations have become essential research tools in all of the sciences. In this, we again see an ultimately mathematical structure becoming a surrogate for reality. We seem to have an almost intuitive notion that mathematics somehow captures features of reality.
 - 1. Geologists, for example, use computer simulations to predict the processes that take place beneath the crust of the Earth. Predictions of the simulations then become the hypotheses of experiments.
 - 2. In this way, computers have influenced the practice of all physical, life, and social sciences.
 - 3. The very availability of computers causes us to identify new kinds of problems and to attempt to solve them in new ways. We can

also avoid simplifying problems because of the availability of computing power.

- B. Since the 1980s and the Four-Color Map problem, mathematicians have used computers as part of mathematical proofs.
 - 1. Part of a proof may read, for example: “Input to a computer... output from a computer.”
 - 2. Does this “shortcut” meet the definition of a *mathematical proof*; that is, to show a line of reasoning to demonstrate that a conclusion is true?

IV. Despite the philosophical questions surrounding the discipline, new forms of mathematics continue to provide fertile areas of exploration for science.

- A. For example, *game theory*, the mathematical modeling of rational choice in either competitive or cooperative situations of partial or no information, attracted attention during World War II and quickly became a staple of tactical and strategic military planning, political science, and economic theory.
- B. Early in the 20th century, several mathematicians studied a peculiar property of certain algebraic curves: self-similarity. In 1951, Benoit Mandelbrot synthesized these ideas, along with his own, into what became a new branch of mathematics, *fractals*, the geometry of self-similar shapes.
- C. No account of science in the second half of the 20th century can omit the influence of mathematics-based *chaos*, or *complexity, theory*.
 - 1. *Chaos theory* is the application of mathematical tools to describe the underlying order of apparently disorderly natural phenomena, such as the weather.
 - 2. In particular, scientists use chaos theory to model the behavior of non-linear systems, which over time, display an exquisite sensitivity to minute differences in initial conditions.
 - 3. Throughout the 20th century, we have become increasingly sensitive to such non-linear, non-equilibrium systems. We have moved away from the 19th-century notion that equilibrium is the norm; we now recognize that many systems can remain in a non-equilibrium state through self-organization.
- D. Finally, especially for the Internet generation, it is necessary to note the development of the mathematical theory of *complex networks*.
 - 1. Just after World War II, the Hungarian mathematicians Paul Erdos and Alfred Renyi created a mathematical model of a randomly connected network. Networks can have different kinds of structures—random connection is just one—and these structures have distinctive properties, quite independent of what they connect.

2. This theory is another example of 20th-century relationalism at work in science. The network of neural cells in the brain, the network of proteins determining cell metabolism, and the network of genes determining the self-organization of amino acids into proteins are all areas of exploration as complex networks.

Essential Reading:

John Casti, *Five More Golden Rules: Knots, Codes, Chaos, and Other Great Theories of 20th-Century Mathematics*.

John Holland, *Emergence: From Chaos to Order*.

Ernest Nagel and J. R. Newman, *Gödel's Proof*.

Supplementary Reading:

Andrew Hodge, *Alan Turing: The Enigma*.

Questions to Consider:

1. Does it matter that, logically at least, mathematics is incomplete and cannot be proven consistent?
2. Do mathematicians explore the properties of mathematical “objects” that exist independently of our experience of them, or do they invent these objects?
3. If the latter, how can mathematics be so fertile in science, which is about experience if not reality; but if the former, how can we know these objects?

Lecture Fourteen

The Universe Expands

Scope: It was only in the early 1920s that other galaxies were discovered. Suddenly, the *universe* was no longer synonymous with the Milky Way, which was no more central to the great scheme of things than the Earth had been thought to be before Copernicus. Five years later, analysis of star light suggested that the universe was expanding. Ten years after that, the Big Bang theory of the origin of the universe, supported by new developments in atomic physics and theories of the life and death of stars, was proposed as an explanation of that expansion. This theory implied a temporal beginning to the universe, however, and was challenged after World War II by the Steady State theory, which explained expansion without a beginning. Observational astronomy later swung support to the Big Bang approach.

Outline

- I. Our understanding of the universe in the year 2000 contrasts dramatically with our understanding in 1900.
 - A. The difference in these two views is not just a matter of scaling up the universe; by the end of the 20th century, we have completely reconceptualized the universe.
 - B. We have used the term *evolution* in describing this survey of 20th-century science. This term applies not merely to the content of the sciences but also to our thinking about nature. Indeed, our brief overview of mathematical thought revealed the evolution of our thinking about thinking.
- II. In 1900, the universe was “homey.”
 - A. In 1543, Copernicus argued that the Sun was the center of the universe and that the known planets rotated around the Sun. The “fixed stars” were far from Earth but close together in space. Copernicus did not know the scale of the universe.
 - B. Between the time of Copernicus and the mid-19th century, astronomers had worked out the scale of the solar system. They knew, for example, that the Moon was about 200,000 miles from Earth and the Sun was about 93 million miles from Earth.
 - 1. In 1838, Friedrich Bessel used the principle of *parallactic displacement* to calculate the distance from Earth to a star.
 - 2. He determined that a star in the constellation Cygnus was 6.2 light years from Earth. (Remember that a light year is about 6 trillion miles.) The distance to this star, 38 trillion miles, gave astronomers some sense of the scale of the universe.

- C. By the early 1900s, the Milky Way was considered to be synonymous with the universe; it was the only galaxy. Nebulae, seen as fuzzy, glowing clouds, were believed to be clouds of gas within the Milky Way.
- D. In 1900, George Ellery Hale, a world-class solar astronomer, received funding from the Carnegie Institution of Washington to build a 60-inch reflecting telescope and an observatory on Mt. Wilson in southern California. Hale installed Harlow Shapley as director of the observatory.
 - 1. Fortunately for Shapley, a woman at Harvard University, Henrietta Leavitt, recognized that the brightness of certain stars varied with regular periods that were correlated with their observed luminosity. These *Cepheid stars* are distributed throughout the universe and can be used as “yardsticks” to calculate distances.
 - 2. Shapley used Leavitt’s techniques, together with a technique for correlating the brightness of stars with their distinctive light spectra, to estimate the distance to the Large Magellanic Cloud at 100,000 light years. Suddenly, the universe had a scale and, for 1916, a jaw-droppingly immense one at that!
 - 3. Shapley also used this technique to estimate the size of the Milky Way and the location of Earth within it. These advances catapulted Shapley to fame, and he left Mt. Wilson to become director of the Harvard University Observatory.
 - 4. In 1919, a 100-inch telescope became operational at Mt. Wilson, and Edwin Hubble became director of the observatory there.
 - 5. In a public debate in New York City in 1920, Shapley aggressively defended the identity of the universe with the Milky Way against recent speculations that nebulae were other galaxies.
 - 6. In 1924, Hubble, using the 100-inch telescope, observed individual stars in the Andromeda “nebula,” revealing that it, too, was a galaxy composed of hundreds of millions of stars and about a million light years from the Milky Way. Hubble could also see thousands more galaxies beyond Andromeda and, soon, millions more. The scale of the universe exploded!
- E. Hubble was far from done.
 - 1. In 1914, a little-known American astronomer named Vesto Slipher had reported a puzzling fact about the light he had analyzed from about a dozen nebulae: The frequencies were shifted from laboratory-based expectations, as if the stars were moving. Slipher’s observations did not receive serious attention.
 - 2. In the mid-1920s, Hubble revisited Slipher’s thinking and collected his own spectra from about 250 of the many galaxies he had discovered. He observed that, except for the nearest, all these galaxies were shifted toward the red end of the frequency

spectrum. Applying the principles of the *Doppler effect*, Hubble concluded that all these galaxies were moving away from Earth.

3. The Doppler effect is a wave phenomenon. Sound waves will seem to be of a higher frequency when traveling toward a listener and a lower frequency when traveling away from the listener, as if the waves are being stretched. In the same way, a light wave traveling away from an observer will be shifted toward the lower frequency, or red end of the spectrum.
4. Hubble also noted that there was a direct relationship between the size of the shift in the spectra and the distance of the galaxy from Earth: the greater the distance, the greater the shift.
5. In 1929, Hubble announced that the universe was expanding!

III. In 1917, Willem de Sitter had informed Einstein that the equations of the general theory of relativity entailed an expanding universe.

- A. Given that Einstein knew of no astronomical evidence to support this conclusion, he modified his gravitational equations to cancel this “spurious” expansion.
 1. In the mid-1920s, the Russian Alexander Friedmann worked out the expanding universe consequences of the general theory of relativity.
 2. Einstein was impressed with Friedmann’s papers, but it was only after Hubble’s announcement that he re-evaluated the general theory of relativity and removed his clumsy modifications.
 3. Georges Lemaître, a Belgian physicist and a Catholic priest, speculated that the expansion implied that the universe had a beginning in time and space from a single point of matter, consistent with Genesis.
- B. Hubble also traced the expansion backwards and estimated the age of the universe at about 2.5 billion years. Estimates of the age of the Earth, based on radioactivity, had put it at about 1.5 billion years.
- C. In 1938, Hans Bethe proposed that stars generated their energy by fusing hydrogen atoms into helium atoms, which gave us some understanding of the evolution of the universe. A year or two later, George Gamow began to build his first formulation of what came to be called the Big Bang theory that the universe originated in a cosmic explosion of matter.
 1. Gamow continued to develop this idea with collaborators, publishing important papers in 1946 and 1948, but the theory could not explain, in a manner that was consistent with quantum theory, *nucleosynthesis*, that is, the synthesis of heavy elements in stars.
 2. At the same time, Fred Hoyle, Hermann Bondi, and Thomas Gold rejected the idea that the universe had a beginning, although they

acknowledged its expansion; they proposed, instead, a *Steady State theory*.

3. The Steady State theory requires the regular creation of hydrogen atoms to maintain constant density as the universe eternally expands. Except for local variations, the universe is essentially uniform in space and time. But this theory, too, requires an explanation of how all the elements are synthesized from hydrogen atoms.
4. Hoyle, with physicists William Fowler and Geoffrey and Margaret Burbidge, worked out a solution to this problem in the mid-1950s, but in the end, the solution reinforced the Big Bang theory! How this development came about is the subject of our next lecture.

Essential Reading:

Brian Greene, *The Elegant Universe: Superstrings, Hidden Dimensions, and the Quest for the Ultimate Theory*.

Helge Kragh, *Cosmology and Controversy*.

Dennis Overbye, *Lonely Hearts of the Cosmos: The Story of the Scientific Quest for the Secret of the Universe*.

Supplementary Reading:

Timothy Ferris, *The Whole Shebang: A State-of-the-Universe(s) Report*.

Questions to Consider:

1. Why do we think that everything there is constitutes a uni-verse, that is, an ordered whole, as opposed to a mere collection of things?
2. How do modern optical telescopes differ as complex instruments from particle accelerators or electron and quantum mechanics-based microscopes?
3. Is the universe expanding, or is expansion merely one way to interpret astronomical data so that the data fit a number of accepted physical theories?

Lecture Fifteen

What is the Universe?

Scope: In the 1960s, the discovery of a universal cosmic background radiation, together with developments in the relativity and quantum theories, resurrected the Big Bang theory of the universe. Pursuing this approach to cosmology has led to increasingly detailed, but often controversial and speculative, accounts of the constitution, age, size, and origin of the universe. For example, after a late-20th-century modification of the Big Bang hypothesis called *inflation theory*, the universe suddenly became far more vast than anyone had imagined and perhaps not unique. It may have been the offshoot of literally no “thing” at all, but of the energy of the vacuum, according to quantum theory. Furthermore, to everyone’s surprise, in 1998, astronomers found evidence, subsequently strengthened, that far from slowing down as had been supposed, some force was causing the expansion of the universe to accelerate.

Outline

- I. We ended the last lecture in the 1950s with the rivalry between the Big Bang theory and the Steady State theory. At about the same time, George Ellery Hale had been aggressively seeking funding to build a 200-inch telescope.
 - A. Hale secured funding from the Rockefeller Foundation to build another observatory in southern California on Mt. Palomar. The 200-inch telescope became operational there in 1949. Hubble was director of this observatory briefly before his retirement and was succeeded by Alan Sandage.
 - B. Sandage inherited privileged access to the 200-inch telescope, along with the “mantle” of Hubble, that is, Hubble’s view of the universe and his techniques for estimating distances in the universe. Sandage also inherited Hubble’s brilliant assistant, Milton Humason.
 - C. Sandage refined and extended Hubble’s methodology, correcting the estimated age of the universe to approximately 11 billion years. Eventually, Sandage would estimate the age of the universe at 18–20 billion years, which put him in rivalry with a younger generation of astronomers who argued that Hubble’s techniques for measuring galactic distances were incorrect.
 - D. Finally, in 1999, a team of astronomers led by Wendy Freeman established the age of the universe at about 13.7 billion years.

- II.** We now pick up the story of the Steady State theory, which had been poised to triumph over the Big Bang theory in the early 1960s.
- A.** In 1958, Geoffrey Burbidge reported radio signals from distant galaxies that seemed to have the energy of a million or more stars.
1. Between 1958 and 1960, a Dutch physicist, Maarten Schmidt, studied these energy sources and gave them the name *quasars*, for “quasi-stellar radiators.” These objects are relatively compact, yet they have tremendous energy. They also seemed to be associated with the centers of the most distant galaxies.
 2. The discovery of quasars was perceived as a blow to the Steady State theory, which asserts that the universe is, on a large scale, uniform at all distances and in all directions. Because of their great distance, quasars seemed only to have formed long ago, implying that the Earth was not uniform.
 3. Astronomers later determined that quasars are massive black holes and that every galaxy, including ours, has a black hole at its core, though not a massive one.
- B.** The second blow to the Steady State theory was the discovery of microwave background radiation.
1. In 1949, Gamow and his collaborators claimed that their theory implied that the universe should be uniformly filled with the aftermath of the Big Bang in the form of microwave frequency radiation and that the temperature of the universe should be about 5 degrees above absolute 0 (5 degrees Kelvin).
 2. In the early 1960s, with Fowler’s solution to nucleosynthesis available, Princeton physics professor Robert Dicke began to re-examine the universe’s “birth” as if the Big Bang theory were true. He challenged his graduate students, among them Jim Peebles and Dave Wilkinson, to work out its consequences.
 3. Peebles filled in a gap in the Fowler nucleosynthesis program and predicted a microwave background afterglow of about 10 degrees Kelvin. The team at Princeton then began to plan an experiment to search for this afterglow but they were “scooped” by two industry scientists at Bell Labs.
 4. There, Arno Penzias and Robert Wilson were developing an antenna that could exchange microwave frequency radio signals with the first communications satellite, Telstar. Penzias and Wilson used an extremely sensitive antenna that had been developed for an earlier project.
 5. In attempting to calibrate this antenna, Penzias and Wilson could not eliminate a background hiss that seemed to come from every direction. Happening upon Peebles’s paper, Penzias and Wilson calculated the temperature equivalent of the background noise at about 3 degrees Kelvin. They called Dicke with the news, and suddenly, the Big Bang theory was resurrected!

- C. Research into the microwave background radiation since that time has given us our oldest picture of the universe. In particular, two satellites launched by NASA, in 1992 and 2002, have enabled us to “see” the universe as it was approximately 380,000 years after the Big Bang.
 - D. Theory required that the background radiation be almost perfectly uniform. By the mid-1960s, however, scientists realized that if that were true, matter would never have clumped together to form stars, let alone galaxies. There must be some non-uniformity in the cosmic microwave background.
 - 1. From the late 1960s, Dave Wilkinson played a central role in the detailed measurement of the non-uniformity of this radiation, termed *anisotropy*.
 - 2. Data from the NASA satellites has revealed minute variations in the background radiation temperature in the range of 10^{-5} degrees Kelvin, and this is consistent with the clustering of matter into stars and galaxies.
- III. Quantum theory strongly suggested that although the Big Bang and cosmic expansion were real, the visible evidence of these phenomena could not be extrapolated back to the event in which the universe originated. We need to use quantum mechanics to understand the origin event at a much deeper level than Gamow’s theory allowed.
- A. In 1980, Alan Guth proposed what he called *inflation theory* to explain why the visible evidence of Gamow’s Big Bang takes the form it does.
 - 1. The quantum theory of the vacuum suggests that a *false vacuum* can exist that contains a tremendous amount of pent-up energy. This energy is “stalled,” initially, but can be triggered and released.
 - 2. Building on this idea, Guth proposed that at 10^{-35} seconds after the Big Bang, the universe underwent an instantaneous inflation in which its size doubled 100 times. In the process, the universe cooled dramatically, from 10^{28} degrees Kelvin.
 - 3. This inflation pulled the universe into a uniform mode with very modest non-uniformities. In that universe, the breaking of symmetries took place that led to the emergence of photons and matter.
 - B. The inflationary moment was powered by a false vacuum. At the time of this occurrence, the universe was about the size of a softball; it then expanded by a factor of 2^{100} . Thus, even the vast observable universe of the late 20th century is only a minute fraction of the entire inflated universe.
 - C. Since 1980, inflationary theory has become the orthodoxy in astrophysics and cosmology. All available empirical evidence is consistent with this theory.

- D. In the past two decades, two comparably dramatic developments have taken place that require reconceptualizing the inflated universe.
1. The first of these was the realization, in the 1980s, that galaxies rotate too fast to hold together. Some other force must hold galaxies together and, indeed, must hold clusters of galaxies together. The consensus view at the end of the 20th century is that *dark matter* is responsible for this stability and that dark matter accounts for more than 90% of the total matter in the universe.
 2. The second dramatic development took place in 1998, when two teams of physicists announced that the expansion of the universe is accelerating. The so-called *dark energy* associated with this acceleration would be the dominant form of energy in the universe. In the next lecture, we'll discuss how we know these mind-boggling facts about the universe.

Essential Reading:

Alan Guth, *The Inflationary Universe: The Quest for a New Theory of Cosmic Origins*.

Brian Greene, *The Elegant Universe: Superstrings, Hidden Dimensions, and the Quest for the Ultimate Theory*.

Supplementary Reading:

Helge Kragh, *Cosmology and Controversy*.

Questions to Consider:

1. Why would scientists prefer the Steady State to the Big Bang theory as a model of the universe?
2. Did Penzias and Wilson discover the microwave background radiation, and what does their experience, and the 1998 “discovery” of the universe’s acceleration, reveal about the relation between theory and experiment in science?
3. Can we truly comprehend a universe such as that described in inflation theory, and what value is a scientific theory that is not comprehensible?

Lecture Sixteen

How Do We Know What's Out There?

Scope: Ideas and theories tend to dominate histories of science, but the fact is that from the beginning of modern science, instruments have played a fundamental role in stimulating ideas and theories and in determining which ideas and theories survive. Successful theories are those whose predictions are borne out by observations, but discoveries are made by instruments. In the 20th century, newly invented instruments disclosed utterly unanticipated cosmic realities. Beginning in the 1930s, with the unexpected discovery of radio-wave emissions from outer space, the array of Earth- and space-based instruments available to astronomers expanded: radio telescopes; infra-red, ultraviolet, X-ray, cosmic ray, and gamma ray telescopes; orbital satellites and interplanetary space probes; radical new optical telescope designs; neutrino telescopes; and gravity wave telescopes. All these revealed a universe vastly more varied and complex than anyone had imagined in 1900.

Outline

- I. How do we know about the universe? Just as we saw in QED and the transition to QCD and in chemistry, we will see that the development of instruments in astronomy has played a substantial role in our theories of the universe.
- II. Before we begin looking at these instruments, we will briefly review the chronology of the universe in the framework of the Big Bang model, adjusted for inflation theory.
 - A. Approximately 13.7 billion years ago, an origin event took place. Only 10^{-43} seconds later, the loops or strings manifested themselves in their full 10-dimensional generality. At 10^{-36} seconds, supersymmetry broke, separating gravity and the Higgs field; the loops or strings contracted down to 3 dimensions. At 10^{-35} seconds, the universe underwent inflation, doubling in size 100 times.
 - B. When the universe was 10^{-20} seconds old, the first photons appeared. At 10^{-10} seconds, matter appeared, first in the form of quarks and leptons, then at 10^{-4} seconds, as protons and neutrons. At 100 seconds, the first elements appeared: hydrogen, helium, and a very little lithium.
 - C. At one month of age, the universe filled with what physicists call *blackbody radiation*, the echo of which was detected by Penzias and Wilson in 1964 as the microwave background radiation. At about 400,000 years of age, photons separated from matter. However, the universe was dark, because the average energy of the photons was below the visible range.

- D. At about 900,000 years, there was light! The first stars formed, and by a billion or so years, there were galaxies. The matter in galaxies evolved into a mix of 90% hydrogen, 9% helium, and 1% everything else, which is what we observe today.
- III. The main instruments for studying the universe were, from the time of Galileo until the mid-20th century, all based on light, including optical telescopes, photographic equipment, and spectrometers.
- A. In 1935, two AT&T engineers were assigned to investigate static on long-distance telephone lines. In the course of their work, they discovered radio signals coming from the Sun and from the center of the Milky Way. This discovery led to the birth of radiotelescopy.
1. After World War II, this became a major branch of astronomy, from which we have gained a great deal of information.
 2. In the early 1950s, for example, Harvard University Observatory invested in a small radiotelescope, which was enough to discover the frequency radiated by interstellar hydrogen.
 3. Over the next decade, radio astronomers discovered hundreds of atoms and molecules in space, including organic molecules and hydroxyl molecules. These findings have significant implications for understanding the origin of life.
 4. By the 1960s, astronomers were using a 250-foot steerable parabolic dish at Jodrell Bank in England and a 1000-foot non-steerable dish in Arecibo, Puerto Rico. These huge instruments offered a critical new window on the universe and revealed that it was different from what we thought it was.
 5. In the 1970s, the United States built a massive radiotelescope in New Mexico. This *Very Large Array* links 27 eighty-foot-wide telescopes in a Y-shaped configuration over miles of the desert. These 27 telescopes are connected using the interferometry principle. The configuration is the equivalent of a single radiotelescope dish that is 20 miles in diameter.
- B. Cosmic rays were a surprise and radiotelescopy opened truly new windows on the universe, but they were just the beginning of discovering the richness of the non-visible universe.
1. Only in the 1960s was it discovered that there were X-ray and gamma ray sources in outer space, as well as sources of neutrinos. The same period of time saw renewed interest in the general theory of relativity, which had predicted gravity waves and, by extension, the existence of a particle called the *graviton*.
 2. These discoveries prompted the development of instruments that could help us explore new aspects of the universe.
- C. The first X-ray satellite, the X-Ray Explorer, was launched in 1970 and immediately validated the prediction of the existence of *pulsars*, or

neutron stars, dense concentrations of matter remaining after the death of a star.

1. Neutron stars had been discovered by Jocelyn Bell, a graduate student, in the output of radiotelescope observations. Bell noted an extraordinary repeated pattern of pulsed signals.
 2. The X-Ray Explorer confirmed the existence of pulsars.
- D. The X-Ray Explorer also validated the existence of black holes. The satellite observed a star in the constellation Cygnus, Cygnus X-1, which orbits around an invisible companion.
- E. Further improvements in telescopes resulted in NASA's Great Observatories series, which put four major satellite telescopes in orbit in the last decade of the 20th century and the first decade of the 21st: the Hubble Space Telescope, the Compton Gamma Ray Observatory, the Chandra X-Ray Observatory, and the Space Infra-Red Telescope Facility. This complex of telescopes has enabled us to observe the earliest stars, galaxies, and galactic clusters.
- F. Another instrument in this arsenal of telescopes is the neutrino telescope.
1. As you recall, the existence of neutrinos was postulated by Wolfgang Pauli during the controversy over the nature of beta decay that took place in the 1930s.
 2. In 1955-1956*, Department of Energy scientists at the Savannah River Complex observed the neutrino for the first time. A few years later, neutrinos were detected using a large tank of chlorine installed deep underground in an abandoned gold mine. Evidence in the 1960s suggested that solar neutrinos changed their character in ways that implied that they had mass.
 3. Subsequently, more sophisticated directional neutrino detectors were constructed, including the Super Kamiokande Detector in Japan and two built by the United States in Antarctica.
- G. Finally, we turn to the gravity wave telescope, which uses the interferometry principle and is capable of detecting a change in the shape of space on the order of 10^{-16} centimeters. NASA and the European Space Agency are planning a project to put three gravity wave telescopes in orbit above Earth; this configuration will be able to detect even smaller changes in the shape of space and may validate the existence of the graviton.
- H. We close this discussion of instrumentation by returning to optical telescopes. Despite advances in other areas, optical telescopes have developed extraordinary new capabilities.
1. Very large, single-mirror, glass-lens telescopes pose almost insuperable mechanical problems. One solution to these problems is a computer-controlled, multiple-mirror design, such as the two 6-segment, 10-meter telescope mirrors for the Keck Observatory

on top of Mauna Kea volcano in Hawaii. Twice each second, computers adjust the shape of the mosaic mirror to within 4 nanometers of the perfect shape of a single 10-meter-diameter mirror.

2. In 1999, an adaptive optics system for the Keck configuration virtually eliminated the distorting effects of the atmosphere. In addition, the two main telescopes, plus two smaller 2-meter-wide “satellite” telescopes, are linked by the interferometry principle.
3. In 2000, the Keck telescope observed the transit of a planet across the face of a star 153 light years away at exactly the time predicted by theory!
4. The Keck Observatory technologies are representative of world-class practice at the close of the 20th century. Other facilities with comparable equipment include the European Southern Observatory and the Inter-American Observatory in Chile, high above the Atacama Desert.

Essential Reading:

Walter McDougall, *The Heavens and the Earth: A Political History of the Space Age*.

Wallace Tucker and Karen Tucker, *The Cosmic Inquirers*.

Questions to Consider:

1. Should the proliferation of new types of telescopes other than optical ones make us feel confident that *now* we are receiving all the signals that the entities that make up the universe are emitting?
2. Is there a limit to the development of new instruments, and how will we know when we’ve reached it, or is this a self-perpetuating research “industry”?
3. How can the public better share in the beautiful and important knowledge continually being created at its expense but now in the possession of small communities of experts?

* *Erratum*: On the tape, the professor inadvertently stated that Department of Energy scientists first observed the neutrino in 1965-1966. The correct date is 1955-1956.

Lecture Seventeen

From Equilibrium to Dynamism

Scope: In 1900, the dominant view of the Earth among geologists was that the continents had formed as they were, where they were, when the Earth cooled from its initial molten state and that the surface of the continents was the result of those forces, and only those forces, currently acting. American geologists, especially, remained tenaciously committed to this view even as European geologists began to favor a view that the continents had been in motion since they formed, colliding, merging, separating, and migrating around the world over the course of eons. Finally, in the 1960s, empirical observations provided compelling support for what had been called *continental drift*, as well as a mechanism to explain how and why the continents drift. The story of the resulting, now dominant, theory of plate tectonics offers fascinating insight into the process of theory creation and gives us a very different account of the Earth than the one we had in 1900.

Outline

- I. Conceptually speaking, the change in our understanding of the Earth between 1900 and 2000 is comparable to the change in our understanding of the universe in the same period.
 - A. In 1900, the Earth was considered to be stable, at or approaching equilibrium as it cooled from its initial molten state.
 - B. By 2000, the Earth was conceived to be a violent, dynamic *system*.
 - 1. Its interior is roiled by convection currents of lava, driven by the 6000-degree heat of its solid iron core.
 - 2. The continents are a mosaic of colliding “plates,” pushed apart by magma welling up from the ocean floor.
 - 3. The Earth’s magnetic field is continually shifting and episodically reversing.
 - 4. Its daily rotation is slowing as the moon spirals outward.
 - 5. Massive open-ocean currents affect the biosphere and the atmosphere.
 - C. We also now know that the Earth is a working part of a larger system, encompassing the solar system and the universe.
- II. In 1900, American geologists were unanimously committed to a theory that explained the surface features of the Earth as the result of contraction, as the Earth steadily cooled from its initial molten state, together with erosion and sedimentation.
 - A. At the time, the British physicist Lord Kelvin had convinced many biologists and geologists that the Earth was, at most, 100 million years

old and was steadily losing heat. But this notion turned out to be wrong and profoundly misleading.

1. The discovery of radioactivity by Becquerel in 1896 and, in 1903, the announcement by Marie Curie of the enormous amount of energy released by radioactivity, had major consequences for biology and geology.
 2. In 1913, Arthur Holmes published the first absolute dating scale in geology, putting the age of the oldest known rocks at 1.5 *billion* years. This implied that the Earth had an internal energy force that acted to sustain a non-equilibrium state.
- B.** Accumulating evidence challenged the *isostasy theory*, which assumed that the Earth's major formations—oceans, continents, and mountains—were at or approaching equilibrium.
1. For instance, the region of Scandinavia was found to be rising, which was attributed to the melting of glaciers. This finding revealed that continental masses were capable of some vertical motion.
 2. Further, geologists studying the Alps noted that the “folding” of the rock strata strongly suggested some lateral force pushing on the continents as mountains formed.
- C.** In 1915, a German physicist, Alfred Wegener, proposed a theory called *continental drift* based on three observations: (a) the jigsaw-puzzle fit of the continents, suggesting that they had, at one time, been joined; (b) the fact that rock strata matched up across continents; and (c) identical plant and animal fossils that were found across ocean barriers. With very few exceptions, American geologists strongly opposed Wegener and his theory.
- D.** In 1928, Arthur Holmes published a paper explaining continental drift as the result of convection currents deep below the continents, which brought magma up through the mid-ocean floor, forcing the ocean floor apart, and in turn, causing the movement of the continents.
1. One major objection to this line of thinking came from the study of earthquakes. Such studies suggested that seismic waves propagated through the Earth as if the Earth were rigid.
 2. Increasing evidence, however, showed that a fluid that flows very slowly could behave like a rigid body. One example is glass.
- E.** In 1923, a Dutch geologist, Felix Vening Meinesz, invented a shipboard instrument that was capable of accurately measuring the strength of the Earth's gravity.
1. Meinesz circled the globe in a Dutch submarine and found that the ocean floors were not in equilibrium, as isostasy required; he confirmed this finding in 1928 on a cruise aboard a U.S. submarine.

2. When World War II broke out, the Navy turned to geologists for help in submarine warfare. The Navy also supported further research on the strength of the gravitational and magnetic fields under the ocean.
- F. Immediately after the war, attention was focused on mapping the magnetic field strength of the Earth.
1. Holmes's idea that magma was constantly pushing up out of the ocean floor suggested that geologists should be able to find evidence of magnetic field "stripes" in the ocean floor.
 2. In the 1930s, scientists had begun to seriously consider the idea that the Earth's magnetic field had changed. After World War II, studies of geological strata confirmed this idea.
 3. In the 1950s–1960s, the U.S. Navy collected enormous amounts of data on the magnetism of the ocean floor. In 1962, an American geologist, Harry Hess, who had gained access to the Navy's data, published the pioneer version of what came to be called *plate tectonics*.
 4. Hess himself discovered the eroded remains of undersea volcanoes, which supported his theory. Others found valleys and volcanoes along the mid-ocean ridges, revealing that the ocean was geologically active.
- III. We now know that the continents and oceans are about 60–80 miles thick, and they both rest on a layer of material on top of the Earth's mantle that is not quite solid, yet not quite viscous.
- A. The magma welling up from the mid-ocean floor cools and creates new ocean floor, which pushes the old ocean floor outward. The old floor moves over a period of tens of millions of years, pushing on the edges of the continents.
 - B. Through a process called *subduction*, the old ocean floor material is pulled under the continental crust. The continent itself is moved at about the rate of an inch a year.
 - C. The ocean crust is pulled through the semi-solid/semi-viscous layer into the mantle. There, the crust is melted into mantle material and wells back up through the mid-ocean floor. This cycle takes 100–200 million years.
 - D. In 1968, Hess's qualitative theory of plate tectonics was given a mathematical formulation. In the 1970s, plate tectonics became the orthodox opinion of the state of the Earth.

Essential Reading:

Naomi Oreskes, *The Rejection of Continental Drift: Theory and Method in American Earth Science*.

———, *Plate Tectonics: An Insider's History of the Modern Theory of the Earth*.

Questions to Consider:

1. What was so threatening about the hypothesis of continental drift that it provoked decades of opposition in spite of considerable supporting evidence?
2. Why does the assumption of equilibrium have such a powerful hold on our thinking about natural processes?
3. How is our sense of the rationality of science affected by recurring episodes like the discovery of radioactivity, in which fundamental changes in concepts, principles, and theories are triggered by accidents?

Lecture Eighteen

Subterranean Fury

Scope: The Earth as described by plate tectonics is in turmoil beneath a comparatively placid surface, a turmoil driven by a solid iron core almost as hot as the surface of the Sun. But 20th-century earth science also began to view the planet as a system. To understand any part required understanding the relationships among the constantly changing atmosphere, global ocean current circulation, evolving biosphere, moving crust, churning mantle, and rotating liquid and solid cores, as well as the Sun, the Moon, and the solar system as a source of gravitational forces, electromagnetic fields, charged particle streams, and material objects, collision with which has profoundly altered the Earth's evolution.

Outline

- I. The story of the rise of plate tectonic theory is fascinating for the insight it offers into the evolution of scientific thinking over the period from 1900–2000, but the picture of the Earth that emerges is even more fascinating.
 - A. By the end of the 20th century, every aspect of the Earth, from its solid core to the uppermost reaches of its atmosphere, was viewed as “alive,” continuously driven by the play of awesome forces.
 1. By the 1990s, the core of the Earth was determined to be a solid sphere, at least 90% iron and about 1400 miles in diameter, under a pressure more than 3.5 million times that of atmospheric pressure, and at a temperature of almost 6000 degrees Kelvin, the same as the surface temperature of the Sun!
 2. The temperature of the core is largely the primordial heat from the Earth's initial formation. It is what maintains the Earth in a non-equilibrium condition, drives the turbulence beneath the surface of the Earth, and serves as the engine of the Earth's surface geological activity.
 - B. The solid core is surrounded by a liquid iron shell about 1400 miles thick, roiled by convection currents that carry heat from the inner core below through to the mantle above.
 1. Scientists speak of a “meteorology” of the liquid core, as if it had weather systems, including constant “storms,” that can be detected through global networks of seismic detectors.
 2. Above the liquid core is the mantle, which is approximately 1800 miles thick.

- II.** We will return to the interface between the liquid core and the mantle, but first, we will explore the surface features of the Earth.
- A.** The continents and the ocean floor are made of rock and are, essentially, rigid. The continental crust tends to be formed of silicate rock types, and the oceanic crust is largely basalt. Both the continental and ocean crusts “sit” on top of a 70- to 80-mile-thick band of rock that is not quite solid but not quite molten, called the *asthenosphere*.
 - B.** As we discussed in the last lecture, the ocean crust is constantly pushed outward by the upward flow of lava from the mid-ocean ridges. It is then pulled under the continental crust and back into the mantle by a process called *subduction*. This crust is significantly cooler than the mantle material and, thus, sinks.
 - C.** The mantle extends 1800 miles down to the Earth’s outer core of liquid iron, but it is divided into two parts: the upper mantle, which is 400 miles thick, and the lower mantle, which is 1400 miles thick.
 - 1.** Most of the subducted ocean crust becomes molten in the upper mantle and begins the process of re-circulating.
 - 2.** Some crust material continues through the upper mantle unmelted until it reaches the boundary between the lower mantle and the liquid core.
 - D.** The interface between the lower mantle and the liquid iron core is about 120 miles thick and is considered by geologists to be the most dynamic and chemically reactive place on Earth.
 - 1.** No material can move from the liquid iron core to the mantle; thus, the heat from the liquid core can be transferred across this interface only by *conduction*.
 - 2.** This heat creates convection currents in the mantle, which in turn, cause the upwelling of magma at the mid-ocean ridges.
- III.** In the past 10 years, geologists have learned that mantle “jets” are created when some of the ocean crust material sinks to the boundary of the lower mantle and the liquid iron core before melting.
- A.** These jets shoot all the way to the surface, erupting in volcanoes or, in the case of Yellowstone National Park, hot springs.
 - B.** Keep in mind that these jets are fixed in place even as the continental plates move. The hot springs in Yellowstone were, at one time, in Oregon.
 - C.** Another illustration of this phenomenon is found in the Deccan Traps, a vast area of India covered by the remains of molten lava. A hot spot under Reunion Island today was once under the Deccan Traps.

- IV. The 20th-century systemic view of the Earth embraces, in an integrated way, interactions among the oceans, the biosphere, the atmosphere, and the body of the planet.
- A. The study of the deep ocean had to await technologies that became available only in the course of the 20th century.
 - B. With the aid of satellite observing platforms and research vessels, massive ocean currents have been observed that affect the planet's climate and life cycles.
 - 1. Open-ocean currents transport huge quantities of water, up to 50 million cubic feet per second, typically bringing deep Antarctic water to the Arctic, where it sinks and returns in a constant circulation across the equator.
 - 2. These currents generate in their wake vast eddies, which generate smaller eddies in a hierarchy, mixing cold water that is rich in nutrients with warm water, transporting heat along with water, and affecting the climate and ecologies.
 - 3. The atmosphere, too, has only begun to be understood dynamically and as a single, evolving global whole in the 20th century, in continual interaction with the oceans, land, and Sun.
 - 4. In the late 1970s, marine geologists observed hydrothermal venting along the mid-ocean ridges and, to their amazement, discovered hundreds of new species and hundreds of new genera of plants and animals.
 - 5. In 1991, the research submersible *Alvin* observed and monitored an undersea volcanic eruption at the East Pacific Rise and found that as soon as the murderous lava flow eased, plants and animals swiftly recolonized the area, creating a dense, diverse ecology. More recently, it has been discovered that this life returns at temperatures of over 250 degrees.
 - 6. Some scientists believe that life may have originated deep in the ocean surrounding hydrothermal vents, not in water near the surface.
 - C. Atmospheric studies have also changed dramatically since John Dalton began studying the physical mixing of oxygen, nitrogen, and carbon dioxide in 1806.
 - 1. As with open-ocean currents, only in the late 20th century was it realized that global atmospheric currents routinely transport across continents and oceans, not just precipitation, but seeds, insects, dust, sand, pollutants, bacteria, and viruses.
 - 2. The atmosphere is driven by the heat engines from below and above and is affected by ocean currents, as well as our own activity. Thus, the atmosphere links the world in a complex network.

- D.** Because of these interconnections among the oceans, the biosphere, the atmosphere, and the planets, science has been pushed toward a systems perspective of the Earth.
1. What we have said about the Earth also applies to the general theory of relativity and quantum theory; each of those theories told us about interrelationships that we had not appreciated earlier. The general theory of relativity, for example, told us that space, time, matter, and energy are intimately interconnected.
 2. The idea of the Earth as a system became a central theme of 20th-century science and was manifested in the environmental movement.
 3. The widespread reaction to ozone-layer damage is one illustration of systems thinking in the public consciousness, as is the current issue of global warming.
 4. As we'll see in the next lecture, the Earth itself is just one node in a much larger, extraterrestrial system.

Essential Reading:

John McPhee, *Annals of the Former World*.

Naomi Oreskes, *Plate Tectonics: An Insider's History of the Modern Theory of the Earth*.

Questions to Consider:

1. Does plate tectonic theory imply that we are doomed to being helpless victims of episodic calamities caused by the churning mantle?
2. What happens to the Earth's climate zones as the continents move? Are they permanent or do they move, too?
3. Is the total geosphere-ocean-biosphere-atmosphere system so massive that human activity can be dismissed as too puny to affect it, or might human activity upset a delicate balance, with catastrophic consequences?

Lecture Nineteen

Solar System Citizen

Scope: The exploration of space from the 1960s on deepened our understanding of the Earth immeasurably by embedding Earth science in the broader sciences of the Sun, the solar system, and the cosmos. The contrast between system-based Earth science in comparative planetary perspective and 1900-style geology captures many essential features common to the evolution of the physical, life, and social sciences in the 20th century. As with cosmology and quantum theory after 1930, an appreciation of the instruments used to gain knowledge is as important to understanding science as is an appreciation of the knowledge gained.

Outline

- I. By the end of the 20th century, our conception of the Earth had changed dramatically, in the direction of a dynamic terrestrial system.
 - A. The dynamism and the system concept are core innovative features of 20th-century Earth science.
 1. Energy inputs from the Sun and from the Earth's extremely hot core maintain the terrestrial system in a nonequilibrium state, characterized by constant dynamic interactions among the geosphere (the crust-mantle-core subsystem), the oceans, the atmosphere, and the biosphere.
 2. The word *ecology* was invented in the 1880s by Ernst Haeckel but not employed in its current sense until the 1920s. In the 1930s, the term *ecological system* was introduced, and the first plant and animal interactive environmental studies were published.
 3. The last piece of the puzzle was acceptance that human behavior was also a factor in local and global ecologies. Rachel Carson's 1962 *Silent Spring* was a watershed in this regard, as reflected in the rise of a popular environmental movement.
 - B. Recognition that the terrestrial system was itself a subsystem within a cosmic extraterrestrial system is a major 20th-century achievement.
 1. Recognition in the 19th century of the extraterrestrial origin of meteorites followed a long and bitter controversy.
 2. Beginning with cosmic rays in the 1930s, it was discovered that the Earth is bathed in matter and energy from the Sun, the solar system, and distant sources inside and outside the Milky Way.
 3. Besides cosmic rays, the Earth receives charged particles from the solar winds and neutrinos, the most numerous particles in the universe.

4. In addition to the obvious solar radiation and starlight, the Earth is bathed in radio frequency waves, X-rays, gamma rays, and very likely, gravity waves.
 5. In 1958, America's first satellite discovered the Van Allen radiation belts that buffer the Earth from the Sun's violent eruptions of charged particles.
- II.** If the Earth is conceived as an evolving, dynamical system, then the system must include elements beyond the Earth.
- A.** The Sun and the Moon exert subtle, though vital, influences on the Earth. The solar system, too, has played a critical role in the Earth's history and fate.
1. In 1930, Sidney Chapman proposed that the ozone layer was created by chemical reactions in the upper atmosphere driven by ultraviolet radiation from the Sun that blocked much of that life-damaging radiation from reaching the surface.
 2. The planet Jupiter has shielded the Earth through much of its history from asteroid-like particles and comets that rained toward the Sun from the Kuiper Belt. The gravitational field of Jupiter attracted many of these rocky objects, preventing them from hitting the Earth.
 3. In 1979, Luis Alvarez proposed that a collision with a comet or asteroid caused the mass extinction that ended the dinosaur era and made possible the evolution of mammals. This suggested that the four other known mass extinctions in the 600-million-year-history of multi-cellular life on Earth also were triggered by such collisions.
 4. The Moon's presence stabilizes the Earth's rotation on its axis, and the event that created the Moon may have thinned the Earth's early atmosphere so that life evolved as it has.
- B.** Finally, the universe as a whole played, and plays, a determining role in the Earth's fate.
1. This idea is consistent with the Big Bang theory, which links the chemical composition of the Earth to the broader evolutionary history of the universe as a whole.
 2. The formation of the solar system may have been triggered by the shock wave from a nearby supernova.
 3. In 2003, it has been suggested that one of the five mass extinctions of life on Earth was triggered by the radiation from a distant supernova explosion, which caused the Sun to flare and changed Earth's atmosphere in a way that shut down photosynthesis.

- III.** Understanding the Earth thus entails understanding the network of its extraterrestrial relationships, which is what space science is about.
- A.** Less than 10 years after a RAND Corporation report affirmed the possibility and desirability of artificial satellites, a new era in space science began, in October and November 1957, with the launch of Sputniks 1 and 2, followed in 1958 by the first U.S. satellites, Explorer and Vanguard.
1. In 1960, the Transit, Tiros, and Echo satellites were launched, pioneering accurate Earth surface position location, weather monitoring, and satellite-based communications, respectively. Landsat 1, relaying color and multi-spectral images of the Earth from orbit, was launched in 1972.
 2. By the 1990s, Transit had evolved into the Global Positioning System; Tiros, into continuous global satellite-based weather forecasting; and Echo, into global, satellite-based radio, TV, telephone, and data communication systems.
 3. The Russians put the first space station, Salyut, into orbit in 1971, and the Americans followed in 1973 with the short-lived Skylab. In 2000, the International Space Station went into operation, rounding out a century in which the possibility of space exploration began as the stuff of science fiction.
- B.** Research scientific satellites and space probes, with no practical applications, have expanded our understanding of the Earth's place in the solar *system* and the universe. These include the astronomical satellites discussed in earlier lectures, culminating with the Satellite Infrared Telescope Facility, which gave us a glimpse of the earliest stars and galaxies formed after the Big Bang.
- C.** Finally, we have launched space probes that have left Earth's orbit and explored the inner planets all the way out to the Kuiper Belt.
1. The Apollo manned lunar landings were the most dramatic expression of the first phase of space exploration, which included numerous earlier probes launched to the Moon beginning in 1959 and successful launches to Mercury (1973, Mariner 10), Venus (1978, Pioneer; 1983–1984, Venera 15/16; and 1990–1994, Magellan radar-mapping mission), Mars (1976, Viking Landers 1 and 2), and the outer planets (1977, Voyagers 1 and 2).
 2. The Mars Global Surveyor in 1996 and the Pathfinder Rover mission of 1997 paved the way for the 2003 Mars Express of the European Space Agency (ESA) and 2004 NASA Mars Odyssey missions, both with orbiters and air- and soil-science-packed landers.
 3. The Galileo probe, launched in 1989, arrived at Jupiter in 1996 and, for years, collected data about Jupiter and its moons Europa, Io, Callisto, and Ganymede. In 1997, the joint NASA-ESA Cassini

mission to Saturn was launched for a close-up study of that planet and its moons, including landing a probe on Titan, with its orange atmosphere suggesting oceans of hydrocarbons beneath an icy crust.

4. Voyagers 1 and 2 sailed past Uranus and Neptune to Pluto, and now, Voyager 1, still transmitting data, is moving beyond Pluto through the Kuiper Belt and into interstellar space.
- D. This range of accomplishment—and in less than 50 years from the first unmanned orbit of the Earth—has been supplemented by the collection or sampling of material from the Moon, Mars, Venus, Jupiter, an asteroid, and the tail of a comet, as well as particles from the interstellar wind and solar wind.
- E. What have we learned for our NASA dollars?
1. First, we have gained a much greater understanding of the universe. Without the satellites that showed us the microwave background radiation, we would not have had the detailed development of the Big Bang theory that we have.
 2. We have learned that the Earth's history is its evolutionary history as a part of the solar system, and that its future will be determined at least in part by the future of the solar system.
 3. We have learned that we *can* explore space, directly and indirectly, and that without understanding what is beyond the Earth, we cannot understand what is on and within the Earth.
- F. Our investment in space exploration has been substantial, and it was only made possible by government programs operating with the long-term support of the public. In our next two lectures, we will explore the relationships among science, technology, and society that are reflected in this kind of government commitment and public support.

Essential Reading:

Luis Alvarez, *Alvarez: Adventures of a Physicist*.

Peter J. Bowler, *The Earth Encompassed: A History of the Environmental Sciences*.

J. R. McNeill, *Something New under the Sun: An Environmental History of the Twentieth Century*.

Supplementary Reading:

Rachel Carson, *Silent Spring*.

An excellent resource for the history of space exploration is the web site maintained by NASA: www.spaceflight.nasa.gov/history.

On comparative planetology, see the web site maintained (in English) by the Institute for Planetology at the University of Muenster in Germany: <http://ifp.uni-muenster.de/links/worldlnk.phtml>.

American Scientist, the magazine of Sigma Xi, the Scientific Research Society, is an outstanding source of excellent, professionally prepared articles for non-specialist readers on all aspects of science.

Questions to Consider:

1. How does recognizing the dependence of the Earth's fate on its status in a hierarchy of extraterrestrial systems affect our sense of the position of life in the universe? Of human life in the universe?
2. Does making the Earth a part in a greater whole diminish or enhance its status? On what grounds?
3. What is the value to society of our exploration of space, and using what criteria can it be said to be "worth" the financial expenditure?

Lecture Twenty

Science Organized, Adopted, Co-opted

Scope: The practice of science, its scale and its scope, changed dramatically in the course of the 20th century, as did the relationship of science to government, industry, and society. In the United States, by mid-century, the university had become the primary setting for scientific research. The gifted “gentleman” pursuer of knowledge of nature had virtually disappeared, displaced by people who practiced science for a living, either at a university or at a government-, industry-, or foundation-funded research laboratory, but even then, only after acquiring appropriate credentials at a university. First in the physical sciences, then in the life and social sciences, the cost of doing science grew exponentially. Along with this increase came an increasing dependence on external funding and, inevitably, a concomitant influence on science of the goals and values of its funding sources—after World War II, primarily the federal government. In the context of mass anti-establishment protests in the 1960s and 1970s, this led to an attack on the very concept of objective knowledge that ballooned into what was called the *Science Wars* of the 1990s.

Outline

- I. Particle accelerators, fusion research, orbital observatories, and space exploration add up to serious money, perhaps a trillion dollars over the second half of the 20th century. Where did this money come from, why was it spent, and what impact did it have on the practice and content of science?
 - A. In the United States in the 19th century, prevailing opinion held that science was an elitist pursuit and that spending public funds on scientific research was inappropriate. Of course, in a capitalist society, applied science should be funded by industry.
 - B. The U.S. government supported science in a limited number of activities in the 19th century, including mapping the country, conducting research into infectious diseases, and setting regulatory standards for industry.
 - C. At the same time, the United States rapidly made the shift from a primarily agricultural economy to a primarily industrial one.
 1. In 1862, with the South in secession, Congress passed the Morrill Land Grant Act, rewarding states that created engineering colleges with gifts of large tracts of public land.
 2. The impact over the next half century was dramatic: The number of engineering colleges increased from 13 in 1862 to 126 in 1917, and enrollment increased from a few hundred to more than 30,000.

3. The nature of engineering education was an issue of some controversy, ultimately won by those who believed that engineering should be based on science, rather than those who saw the basis of engineering in the workshop.
 4. This new model of engineering education, in turn, created a significant demand for physicists, mathematicians, and chemists as faculty at engineering colleges. Further, American universities were, increasingly, requiring research as a condition of employment for their faculty members.
 5. Driving this trend was, of course, industry, now organized around the corporations that dominated electrification, transportation, communication, and mass production.
- D.** Shortly before U.S. entry into World War I, George Ellery Hale, who was largely responsible for the private funding of four world-class telescopes between 1897 and 1949, tried to convince the U.S. government to organize the nation's academic scientists as a resource for the war effort.
1. Hale failed in this political effort, however, in the face of reluctance to give public monies to academics. Instead, technical knowledge for military needs was organized around engineering, under industrial leadership.
 2. In the 1920s and early 1930s, a second effort by Hale to create a national research council funded jointly by government and industry also failed.
- II.** The situation in Europe was substantially different from that in the United States.
- A.** In Germany, government-funded research institutions in "pure" and applied science had been established by Bismarck and were flourishing, together with industry-funded laboratories.
1. In 1900, Germany was the world leader in technology-based industries and in physical scientific research and mathematics. Germany was also the world leader in harnessing scientific knowledge for military applications.
 2. The United States, Britain, and France resisted this model and, as a consequence, were grossly unprepared for World War I.
- B.** A nation that did not resist the German model was Japan, which became a world military and industrial power in less than 100 years.
- III.** World War II transformed the conduct and organization of science in the 20th century.
- A.** The German persecution of Jews and socialists resulted in a massive shift of technical expertise from Germany to the United States and Britain. The scientists and mathematicians who came to the United

States trained their students in the style and techniques of research that they had developed in Europe.

- B.** Further, in 1940, Vannevar Bush, president of the Carnegie Institution, a former MIT professor, and a pioneer of analog computers in the 1920s, did what Hale had been unable to do a decade earlier. Bush convinced Roosevelt to organize the nation's academic scientists in the interests of national security.

 - 1.** Roosevelt created the National Defense Research Council, with Bush as its head; within in a year, that organization had become the Office of Scientific Research and Development (OSRD).
 - 2.** Bush began to organize a network of the finest scientists in the country into committees to address specific problems with military applications.
 - 3.** The most famous of these efforts was the Manhattan Project, which resulted in the atomic bomb. Perhaps of even greater significance for the war was the research conducted at MIT's radiation laboratory, where radar and electronic countermeasures were developed and improved.
 - 4.** Operations research, what we now call *systems analysis*, was applied to military tactics and planning under the aegis of the OSRD. The OSRD was also involved in developing techniques for manufacturing penicillin in large volumes and at low cost.
- IV.** The legacy of Vannevar Bush lay in his focusing of scientific expertise to solve problems for the government and the military.

 - A.** Bush also authored a report, entitled "Science: The Endless Frontier," outlining his vision for America's science policy in the wake of World War II. This report asserted that America's future was critically dependent on technological innovation, which was itself dependent on sustaining basic science. We could not return to the prewar policy.
 - B.** One result of Bush's report was the creation of the National Science Foundation (NSF), despite a vicious political battle from 1946–1950, again, over the issue of using public funds to support basic science. Since the organization's inception, the budget of the NSF has not been a significant factor in the total post-World War II federal budget for scientific research.
 - C.** The federal government currently supports approximately 600 laboratories that are largely focused on applied science. Of course, the Department of Defense, Department of Transportation, Department of Energy, Department of Agriculture, National Institutes of Health, and NASA distribute billions of dollars, overlapping areas of applied and basic research.

- D. One other consequence of the government's investment in scientific research is that universities have become dependent on federal funding to maintain their integrity as institutions.
- E. Finally, in the 1960s, with widespread anti-establishment sentiment, scientists, too, became a focus of attack, because they were perceived to be in league with government and industry. Concurrently, science experienced an intellectual critique, which had been absent in the past, that questioned its absolute objectivity. In the 1980s, this questioning led to the Science Wars, which will be the subject of our next lecture.

Essential Reading:

Mario Biagioli, *The Science Studies Reader*.

Stephen H. Cutcliffe, *Ideas, Machines and Values: An Introduction to Science, Technology, and Society Studies*.

Ian Hacking, *The Social Construction of What?*

Questions to Consider:

1. What should the relationship be between government institutions and scientific research?
2. In a democracy, who should determine how public monies should be distributed to support what kinds of research?
3. Given the profound social impact of scientific knowledge and its applications, what role can the public play in influencing the direction of research?

Clarification: On the tape, the professor states that the Japanese navy sank the Russian Pacific fleet. The Russian fleet destroyed in the Pacific by the Japanese at the Battle of Tsushima Straits in 1905 was the Baltic fleet, transferred to the Pacific to engage the Japanese.

Lecture Twenty-One

Techno-Science and Globalization

Scope: The entanglement of 20th-century science with society is exemplified in the rise of what came to be called “techno-science,” that is, science-based technological innovation. This alliance among science, engineering, and industry resulted in marketplace success that drove the need for more new science in order to generate further innovations in what sometimes seemed to be an endless cycle of wealth creation. Early-20th-century innovations were primarily engineering achievements, loosely indebted to scientific theory. But the growing power of chemistry and of physics to create commercial (and military) value created a whole new dynamic, not just in the relationship between science and engineering, but in the relationship between technical knowledge and innovation, correctly understood as the selective exploitation of technical knowledge driven by social and market values. Innovation, by the 1970s, was widely accepted as necessary for economic growth and quickly became a global phenomenon. The social, political, cultural, and economic implications of this globalization, in turn, provoked political and cultural responses to innovation and its social infrastructure.

Outline

- I. One of the most important of all scientific developments in the 20th century was not a theory or a discovery, but the new relationship between science and society.
 - A. This change is not merely external to science. The organization, practice, and content of science all changed dramatically, especially in the second half of the 20th century, as the scale of science grew. This increasing scale was associated with the shift of dominance in scientific research to the United States in the post-World War II period.
 - B. One of the elements behind this shift was the notion, especially in the United States, that post-secondary education was a natural expectation for everyone. The G.I. Bill of Rights played a role in creating this expectation.
 - C. The shift of dominance to the United States spawned a new, large-scale approach to science, engendering what has been called “Big Science.” The resulting capital-intensive projects transferred the OSRD wartime experience to peacetime.
 - D. After World War II and under the influence of the United States, science also went global to a greater degree than it ever had before. The so-called “Science Wars” of the 1970s–1990s* were between the

view that science incorporated culturally specific intellectual and value prejudices and thus was only an interpretation of experience and the view that science is universal and an account of reality.

- E.** When President Eisenhower left office, he warned the nation that we had created a military-industrial complex that could easily result in the pursuit of self-serving initiatives by either party. Eisenhower's warning should have included the universities.
 - 1.** Increasingly in the 1960s–1970s, federal funding from the Department of Defense and Department of Energy for direct and indirect military applications was flowing into the universities and transforming them.
 - 2.** Universities were forced to become dynamic in science, engineering, and the social sciences.
 - 3.** Not surprisingly, 40–50 research universities emerged as dominant in terms of federal funding.
- F.** The relationship between government and science also became politicized.
 - 1.** In the wake of Sputnik, Eisenhower recognized the need for a Presidential Science Advisory Committee (PSAC), which Kennedy implemented and used extensively for science policy advice.
 - 2.** Because of its support for the Nuclear Test Ban Treaty and opposition to the Anti-Missile Defense Plan, PSAC was disbanded by Nixon during his administration.
 - 3.** In one of his last acts as president, Gerald Ford formed the Office of Science and Technology Policy, which became operational under Carter.
 - 4.** Given these political aspects of the government-science relationship, it is often difficult to separate scientific advice from political positions. A perfect example of this difficulty is seen in the attitude of the U.S. government toward global warming.
- G.** The suspicion that science has a political dimension is one of the issues that kept the federal government from funding scientific research up until the mid-20th century.
- II.** In the 20th century, the public began to broadly identify science in general with truth.
 - A.** In World War I, for example, psychology received a boost when the army turned to this science for assistance in testing recruits. The Stanford-Binet IQ test was developed initially to screen out those who were intellectually incapable of serving in the military.
 - B.** In the 1920s–1930s, U.S. universities saw a tremendous increase in the study of social science, political science, economics, and management

science. This is indicative of the shift in the American economy from an industrial base to a service base.

1. This shift was already manifest in the 1920s. As government and corporations grew, the demand for managers and bureaucrats grew.
 2. The universities were given the social task of broadening the student base to produce these middle managers. Again, this required more faculty in various specialties, who were, in turn, required to do original research.
- C. To appreciate science as an intellectual and social phenomenon in the 20th century, we must look at the sciences as a whole. The study of social science was also caught up in this broad identification of science with knowledge and truth.

III. We conclude this lecture with a discussion of the progressive intensification of the role of science in technological innovation.

- A. The question of what the relationship between science and society should be was not an issue for the public at large before World War II. Until that time, science was primarily an intellectual activity with a few applications associated with engineering.
- B. After World War II, questions were raised about the proper place of an industrial corporation in society and, in turn, about the proper place of science, which provided industry with its technological innovations.
- C. Before World War II, even radical thinkers had privileged science, setting it apart from their political agendas. After World War II, these thinkers saw that science could not be separated from the impact it had on society.
 1. In the early 1960s, the first academic program in this area, called “Science, Technology and Society,” was created at Cornell University.
 2. One of the goals of this program was to study the ways in which scientific thinking reflects the social environment. Technology was seen as the channel through which scientific thinking is transmitted to society and vice versa.
 3. Such programs spread rapidly at the end of the 20th century in the United States, Europe, and Japan.
- D. One of the most interesting findings of this approach to looking at the relationship between science and society is the recognition that technological innovation is not synonymous with invention.
 1. The internal combustion engine, for example, is the *invention* of a late-19th-century workshop. It becomes an *innovation* when it is transferred to society.

2. The key lies in what happens to an invention before it is accepted into society; that is, the invention is *selectively* implemented.
3. Technological innovation is a social process in which the knowledge of scientists, engineers, and inventors is selectively exploited by corporate managers and government bureaucrats in pursuit of corporate or government agendas.
4. Which inventions are translated into products, how rapidly they are developed, and how they are introduced are all functions of political and social values. This has nothing to do with the mechanisms or theories underlying how an invention works.
5. We should also note that this process is not a one-way street. Society is also responsible for modifications to corporate and government plans for how technology will develop. Society's response to the Internet is one example of its impact on corporate and government thinking.

Essential Reading:

Louis Galambos and J. E. Sewell, *Networks of Innovation: Vaccine Development at Merck, Sharp and Dohme, and Mulford, 1895–1995*.

Steven L. Goldman, *Science, Technology and Social Progress*.

Thomas Hughes, *Networks of Power: Electrification in Western Society, 1880–1930*.

Supplementary Reading:

Thomas Hughes, *American Genesis: A History of the American Genius for Invention*.

Questions to Consider:

1. What is the relation between progress in science and technology and social progress? Does the former always lead to the latter?
2. Have science and technology changed the relationships of power in society?
3. Is the marketplace an effective mechanism for public influence on the innovation process?

* *Erratum:* On the tape, the professor inadvertently stated that the “Science Wars” were in the 1960s–1970s (the correct date is 1970s–1990s) and that by 1927, employment in the service sector exceeded employment in the manufacturing sector (the correct date is 1947).

Lecture Twenty-Two

The Evolution of Evolution

Scope: The “big ideas” in 20th-century life science are associated with evolution, genetics, and molecular biology, and these ideas were intertwined in their own evolution from 1900 to 2000. In 1900, evolution was firmly established among biologists, but natural selection had fallen into disfavor. One problem was time. Based on the prevailing chemical theory of the heat generated by the Sun, the Earth could be only 80–100 million years old, not nearly enough for evolution by natural selection. A second problem was the absence of a mechanism for transmitting to posterity new characteristics “spontaneously” acquired by an organism. The discovery of radioactivity and the recognition that the Earth was billions of years old, the rediscovery of Mendelian genetics, and the invention of population genetics led, by the late 1920s, to a revival of evolution by natural selection and, in the 1930s, to the rise to dominance of neo-Darwinian theory.

Outline

- I. Darwin’s concept of evolution, his “dangerous idea,” was one of the most powerful and radical ideas in all of science.
 - A. Darwin and Alfred Russell Wallace redefined the term *evolution*, which until the mid-19th century, had been used to describe a deterministic development, similar to what a fetus undergoes.
 - B. What did Darwin mean by *evolution*?
 1. It is a process—the continuous, spontaneous, minute variation of offspring from parents, together with natural selection—by means of which, over vast periods of time, all of the multifarious forms of life on Earth have diverged from a common ancestor.
 2. What makes it radical is its contingency, its explanation of design without a Designer, its nominalism, and its assertion of the emergence of true novelty in time.
 - C. These four consequences of Darwinian evolution deserve explication.
 1. Darwinian evolution is contingent in being driven by “spontaneous,” that is, by random, variation.
 2. Natural selection acting on this variation does not merely root out the “unfit”; it leads to structures in organisms that look designed but aren’t.
 3. The category *species* is just a name for Darwin, not a feature of reality. The reality is individual organisms.

4. Because of its contingency, the evolution of life is, in principle, unpredictable: Novelty emerges in time. This stands in sharp contrast to the materialistic determinism of 19th-century science.
- D.** Initially embraced by scientists and intellectuals, by 1900, Darwin's version of evolution was in deep trouble.
1. In 1900, almost all biologists accepted some notion of evolution. At issue was the process by which organisms become as differentiated as they are.
 2. At the same time, the prevailing view that the Earth was only 80–100 million years old made evolution by natural selection alone effectively impossible.
 3. In the absence of an adequate theory of discrete inheritance, spontaneous variation seemed doomed to being “swamped.”
 4. Darwin's insistence that evolution was driven by continuous, small variations rather than by “jumps” was judged by many biologists to be incapable of leading to truly new life forms.
- II.** Darwinian evolution was “rescued” by geology and genetics, and its fate in the 20th century became intertwined with both and with the rise of molecular biology.
- A.** The discovery of radioactivity in 1896 led to Arthur Holmes's 1913 absolute geological time scale of an Earth billions of years old, which revived natural selection as a candidate process for evolution.
- B.** Further, as Darwin realized all too well, evolutionary theory is critically dependent on a coordinate theory of inheritance, one that will preserve variations in only a very few members of a mating population.
1. Gregor Mendel's work was rediscovered in the 1880s-1890s, by scientists looking for the discrete theory of inheritance. Between 1910 and 1930, the Mendelian theory of genetics developed along lines that blurred the distinction between it and Darwinism.
 2. In the 1920s, the genetics community began to look at gene patterns in large populations and to develop mathematical models to predict how genes would spread.
 3. In the 1930s, an explicit synthesis of evolution by natural selection and Mendelian genetics, applied to populations, was effected, and by 1942, Darwinism was the dominant evolutionary theory again.
- C.** The history of evolution in the 20th century is, thus, intertwined with the history of genetics and molecular biology, each of which we will take up shortly.

- III.** The theory of evolution presented a paradox: It displaced the notion of spontaneous generation of life, but if the theory of evolution were correct, then there must have been a time on Earth when life did spontaneously appear.
- A.** In the 1920s, A. I. Oparin and J. B. S. Haldane, proposed that organic molecules spontaneously formed on the young Earth and, under the circumstances then prevailing, formed more complex molecules, until a primitive form of life emerged that was subject to evolution by natural selection.
 - B.** In 1953, Stanley Miller produced self-replicating amino acid chains in his University of Chicago lab. Analysis of the 1969 Murchison meteorite revealed the presence of the same amino acid sequences that Miller had produced.
 - C.** In the 1950s, radio astronomers discovered clouds of organic molecules floating in interstellar space, suggesting that the early Earth already contained the ingredients for life.
 - D.** The discovery in 1977 of mid-ocean thermal vents gave biologists their first glimpse of one form early life took.
 - 1.** At least 3.2 billion years ago, microbial life based on iron and sulfur existed at such vents at temperatures of at least 250° Fahrenheit.
 - 2.** By the late 1990s, experience with self-organizing chemical systems and self-assembling molecular structures led to the suggestion that autocatalytic reactions under such conditions led to the first self-replicating organisms.
 - E.** Evolution is one interpretation of developmental sequencing. It is a dynamic interpretation, that is, driven by forces that result in a nonequilibrium condition. It is also fundamentally historical; without understanding the history of the system, we cannot understand how we arrived in the present and we cannot predict the future with unlimited accuracy.
- IV.** We now take a quick look at what evolutionary biologists think actually happened.
- A.** In the 1950s, 3.5-billion-year-old fossil bacteria called *prokaryotes* were found. These are single-celled organisms without a nucleus that lived in watery environments, perhaps in large mats or webs, in an overwhelmingly carbon dioxide atmosphere.
 - B.** A mutant prokaryote developed photosynthesis and, over a period of hundreds of millions of years, feeding on the CO₂-rich atmosphere of the early Earth, converted it to an oxygen-rich atmosphere.
 - C.** A second mutant, *mitochondria*, stored energy in a molecule, ATP, and could power more complex metabolic processes.

- D. Complex bacteria called *eukaryotes* evolved that captured the mitochondria and developed a nucleus within which the self-replication “machinery” was packaged. Eukaryotes flourished in the now oxygen-rich atmosphere and became the ancestors of all plants and animals, which is why their biochemistry is virtually identical.
 - E. About 600 million years ago, during the Cambrian geological period, the first multi-celled fossils are found.
- V. By 1960, Darwinism had become a “fact” for biologists, but it remained controversial both within biology and within society.
- A. The 1923 *Scopes* trial in Tennessee may have seemed a lamentable manifestation of ignorance to some in the post–World War II era, but even at the turn of the 21st century in America, there are a dozen states that prohibit or severely regulate the teaching of evolution in high school biology classes.
 - B. In 1975, Edward O. Wilson published *Sociobiology*, in which he applied the concept of evolution to human culture and values. This approach, too, provoked a tremendous political response. As we can see, evolution is still a rich and controversial idea.

Essential Reading:

Garland Allen, *Life Science in the Twentieth Century*.

Daniel Dennett, *Darwin’s Dangerous Idea: Evolution and the Meanings of Life*.

E. O. Wilson, *Sociobiology: The New Synthesis*.

Supplementary Reading:

Stephen Jay Gould, *Wonderful Life: The Burgess Shale and the Nature of History*.

Hilary Rose and Steven Rose, *Alas, Poor Darwin: Arguments against Evolutionary Psychology*.

Questions to Consider:

1. Why is evolution such a powerful idea, across the sciences?
2. What are the implications of biological evolution for the meaning of life in general and human life in particular?
3. What is the relation between biological evolution and cultural evolution?

Clarification: Bateson called for the public adoption of the term *genetics* to describe discrete inheritance theory in 1905, but used the term privately earlier. He and others quickly adopted the term *gene* from 1909 on, but it seems first to have been used by Wilhelm Johannsen at a lecture at Columbia University that year.

Lecture Twenty-Three

Human Evolution

Scope: The discovery of fossil human bones in 1856 in the Neander Valley above the Dussell River in what is today Germany sparked a vicious controversy that, even at the close of the 20th century, was still alive. Recognition that these and other fossil bones found in Africa and Asia were the remains of ancient humans and their evolutionary predecessors was slow in coming. Even slower was a consensus on the ancestral “tree” of modern humans. Are we lineal descendants of Neandertal Man or a rival branch of the hominid tree? Did Neandertals die out because they could not compete with *Homo sapiens*; did we aggressively destroy them or, perhaps, mate with them? Meanwhile, discoveries in east Africa put the Neandertal controversies in the context of a multimillion-year evolution of hominids, strongly suggesting that all modern humans originated in and radiated out of Africa.

Outline

- I. As evolutionary theory is deeply intertwined with genetics and both with molecular biology, we *should* turn now to the rise of genetic theory, but the story of our own evolution is too fascinating to defer.
 - A. Darwin was cautious about extending the idea of evolution to man. Not until 12 years after *The Origin of Species*, with the publication of *The Descent of Man* in 1871, did he extend the scientific application of the idea of evolution to human beings and their history.
 - B. Alfred Russell Wallace, the co-discoverer of evolution, never accepted that the theory applied to humans. He believed that cultural evolution was not characterized by the same processes that characterized biological evolution and that the nature of human intelligence was beyond any mutation or variation that could have been associated with a survival advantage.
 - C. Nevertheless, by the end of the 19th century, most scientists believed that humans had evolved, but the consensus was that we had evolved *once*. In other words, at a certain point in the history of life on Earth, human beings emerged. Humans have gotten “better,” but we did not evolve out of a series of creatures that were less human than we are.
 1. Further, different populations of humans on the planet were different because they had become “better” at different rates.
 2. The prejudice was strong that the Europeans were the most advanced. This view underlay and was used as a rationale for 19th-century racism.

3. For the same reason, the overwhelming consensus was that man had evolved on the Eurasian land mass, not in Africa or South America.
- D. In 1856, quarry workers discovered old-looking bones in a cave overlooking the Neander Valley. They called in the local schoolteacher, who recognized the bones as human but not-quite-“us”-human.
 1. Over the next 30 years, an often-vicious debate erupted over whether these were the bones of a diseased “modern” human or of a precursor to modern humans and, if the latter, whether an ancestor or an inferior “cousin.”
 2. Thus was born the Neandertal-versus-*Homo sapiens* controversy, still not fully resolved by 2000, a controversy that reveals a good deal about scientific prejudices.
 - E. After 1908 and the recovery of an almost complete skeleton, Neandertal Man was depicted as a brutish, cave-dwelling ape-man, not an ancestor of *H. sapiens* but a failed branch on the primate evolutionary tree.
 - F. Neandertal bones from a growing number of European sites were soon complemented by fossil remains from Java (1890), southern Africa (1921 and 1924), China (1929 and 1935), and Palestine (1932–1939) that were clearly *not* Neandertal. A minority view began to grow that an ancestral sequence, either linear or branching, was encoded in these confusing fossil clues and, after 1940, that genetics and natural selection might be useful to the decoding.
 - G. After the 1940s, neo-Darwinist biologists began to apply their methodologies to human fossils, reclassifying them into two genera, *Australopithecus* and *Homo*, each with numerous species.
 - H. The neo-Darwinists focused on geographically distributed human populations adapting in different ways to diverse environmental selection pressures that altered their genetic makeup.
- II. The work of Louis Leakey answered several of the remaining questions with the *out-of-Africa hypothesis*.
- A. Louis Leakey began collecting human fossils in the Olduvai Gorge in Tanganyika in the early 1930s, continuing into the 1970s. His wife, Mary, was a partner and their son Richard (following his older brother, Jonathan) carried on to the end of the century.
 1. From the 1960s, the Leakeys, with collaborators, peers, and rivals, unearthed a wealth of fossils that made a case for the African origins of mankind.
 2. In addition to recovering early hominid fossils, in 1966, Mary Leakey established tool-making styles as a characteristic feature of hominids and revealed tool-making as a “proto-industry” that she

named *Oldowan*, once again tying biology and culture together in the study of human evolution.

- B. In 1974, Donald Johanson, digging in Hadar, Ethiopia, uncovered fragments of a female hominid who, after a short but bitter controversy, was accepted, under the name *Australopithecus afarensis*, as the ancestral type of all subsequent hominids. This female, named Lucy, was dated to be about 3.5 million years old.
 - 1. *Australopithecus afarensis* evolved between 4 and 5 million years ago. In the 1980s, a consensus grew that the genus *Homo* branched off some 2 million years ago as *H. erectus*.
 - 2. Almost immediately, *H. erectus* migrated out of Africa to Asia and then to Europe. In 1991 and again in 1999, fossil remains of *H. erectus* 1.7 million years old were found in the Republic of Georgia.
- C. These findings indicate the following sequence: Hominids emerged about 2 million years ago. For 2–3 million years before hominids, there were various species of *Australopithecine* creatures. These creatures existed millions of years after what became the hominid line had diverged from the common ancestor of gorillas, chimpanzees, orangutans, and humans. About 170,000–180,000 years ago, *H. sapiens* evolved in eastern Africa, and they, too, began to migrate.
- D. This sequence was speculative reconstruction until 1987, when two biochemists, Rebecca Cann and Mark Stoneking, applied an insight from genetics and revolutionized paleoanthropology.
 - 1. Every cell contains mitochondria with their own DNA that is inherited through the mother only and, except for mutations, are replicated exactly generation after generation. Cann and Stoneking realized that this provided an absolute marker for matrilineal genealogy.
 - 2. There is an analogous segment on the Y chromosome for males, and by 2000, a strong case had been made that all current humans descend from just three lineages within a breeding population of, perhaps, 2000 *H. sapiens* living in eastern Africa some 150,000 years ago. (In 2002, three skulls found in Ethiopia reinforced this claim.)
 - 3. Two of these lineages remained in Africa, but one migrated out to Asia about 65,000 years ago, then to Europe about 45,000 years ago, and to the Americas in two waves, approximately 25,000 and 12,000 years ago.
 - 4. The Y chromosome dates are a little lower than this but are close, and both imply that all non-Africans descend from a common ancestor about 140,000 years ago.
- E. What happened to the non-*H. sapiens* descendants of *H. erectus*? *H. sapiens* coexisted with *H. neandertalis* in Europe until 30,000–50,000

years ago and with descendants of *H. erectus* in Asia until much more recently. How *H. sapiens* displaced the others is unclear, but it was probably not through interbreeding.

- F. We are also still left with the mystery of what happened between 10,000 and 20,000 years ago that accelerated the cultural development of *H. sapiens*.
1. The record is clear that *Australopithecus* existed for millions of years and did not evolve hominid culture.
 2. Hominids evolved 2 million years ago but show little cumulative cultural development until about 175,000 years ago, when *H. sapiens* emerged.
 3. The pace of cultural development for both *H. sapiens* and Neandertals was extremely slow, until—astonishingly—civilization suddenly was “there,” some 12,000 years ago. In 9000 B.C.E., organized settlements existed with walled towns, trade, and mass production.
 4. What triggered this evolution of human culture? There is some speculation that a mutation leading to the acquisition of speech was the basis of *H. sapiens*’ rise to dominance and the sudden, nonlinear evolution of human culture, especially after the last glacial period.

Essential Reading:

Kurt Lewin, *Bones of Contention: Controversies in the Search for Human Origins*.

Pat Shipman and Erik Trinkaus, *The Neanderthals: Changing the Image of Mankind*.

Supplementary Reading:

Thomas Gossett, *Race: The History of an Idea in America*.

Questions to Consider:

1. Given the cumulative and growing fossil and biological evidence that all humans share a common ancestry, why is racism so persistent a social phenomenon?
2. Considering the slow pace of cultural change over the first 140,000 years of *H. Sapiens*’ existence, how can we explain the rapidity with which “civilization” emerged as the last Ice Age ended some 10,000 years ago?
3. As the out-of-Africa theory of human origins becomes more deeply rooted as a scientific fact, how might it be used to influence global political institutions generally and Africa policies in particular?

Lecture Twenty-Four

Genetics—From Mendel to Molecules

Scope: Gregor Mendel's 1865 paper on the discrete inheritance of certain plant characteristics had been recovered by 1900 by at least four researchers already seeking discrete mechanisms of heredity. A substance in the nucleus of the cell was linked to heredity early in the 20th century, and in the 1940s, this substance was identified as DNA. After Watson and Crick's 1953 discovery of the structure of DNA, exactly what DNA did and how it did it became the preoccupation of biologists studying inheritance and metabolism at the cell and molecular levels. But identifying the double-helix structure of DNA was not the end of the quest; it was barely a beginning. Understanding the replication process, the transfer of instructions from the nucleus to the cell, and the direction of metabolic processes through protein synthesis was yet to be accomplished, and drawing a map of the detailed internal structure of the DNA molecule for individual organisms became a "Holy Grail" for many.

Outline

- I. Between 1900 and 1910, genetics emerged as the dominant theory of inheritance. The story of its rise and development is entangled with the restoration of Darwinian evolution in the 1930s, with the role of biochemistry in biology, and with the rise of molecular biology.
 - A. From the beginning, Darwin recognized that his version of evolution required a complementary theory of inheritance.
 1. How could natural selection alone cause continuous, random, small variations in individuals to accumulate over many generations into new life forms? Why weren't these variations "swamped"?
 2. Meanwhile, a discrete theory of inheritance had been published in 1865 by Gregor Mendel, but it received little attention until the 1890s.
 3. Mendel had concluded that something in the seeds of his pea plants contained the determinant for such properties as skin color and texture. When we speak of *genes*, we mean this kind of discrete determination and transmission of properties.
 - B. In 1900, four individuals in four countries independently recovered Mendel's work in the course of developing their own discrete theories of inheritance.
 1. In 1903, one of these scientists, William Bateson, gave the name *genetics* to such a theory, and in 1909, the name *gene* was given to

- the discrete unit of inheritance by Wilhelm Johannsen*. The gene is analogous in biology to the atom in chemistry.
2. A vicious controversy developed between “loyal” Darwinists, who rejected Mendelianism and developed mathematical models of inheritance patterns to support natural selection acting on continuous, small, individual variations, and the Mendelians, who emphasized mutations, downplayed natural selection, and rejected the heritability of individual variations.
 3. By 1910, evidence accumulated that genes were physically distributed along nuclear structures called *chromosomes*. In the course of cell division, chromosomes divide and recombine (*genetic recombination*), introducing opportunities for new characteristics to appear.
 4. Of particular importance was the creation in 1910 by T. H. Morgan at Columbia University of a genetics research program based on the study of mutations in fruit flies. Morgan found that he could exactly correlate eye color in fruit flies with a particular chromosome.
- C. Note the evolving similarity of gene theory to the atomic and quantum theories in physics, primarily the acceptance of both the gene and the atom as physical realities, along with the use of mathematical models without concern for the underlying mechanisms.
1. In 1908–1909, G. H. Hardy and Wilhelm Weinberg independently developed an equilibrium “law” for genetic inheritance patterns, an equilibrium that would be disturbed by natural selection and selective breeding.
 2. In 1915, H. T. J. Norton extended this, publishing tables of the rate of spread or removal of genes based on selection pressures.
 3. By 1918, natural selection was widely accepted as fundamental, as was the compatibility of evolution and genetics. In 1927, H. J. Muller’s induction of mutations by X-rays convinced most of the reality of genes.
- D. A distinctive feature of genetics research from 1918 to 1930 was a shift of focus from individuals to populations. There is a similarity here to the adoption of statistical descriptions in late-1920s quantum mechanics.
1. By the early 1930s, the work of three men, R. S. Fisher, Sewall Wright, and J. B. S. Haldane, put *population genetics* on a foundation consistent with evolution by natural selection, thereby establishing what Julian Huxley in 1942 called the “modern synthesis” of evolution and genetics.
 2. What is especially interesting in this is that, in another echo of contemporary physics, Fisher, Wright, and Haldane formulated functionally equivalent mathematical models of population genetics from very different assumptions.

- II. Once biologists understood that genes are real, they turned to the question: What are genes?
- A. In 1900, many biologists believed that the basis of life was enzymes, which seemed to be proteins. In 1907, the German chemist Emil Fischer established that proteins were composed of combinations of amino acids.
 - 1. Amino acids are a particular kind of molecule; there are 20 different amino acids, which combine to form the 10,000 different proteins in the human body.
 - 2. Fischer was able to synthesize near-proteins by linking amino acids together, reinforcing a growing conviction that life was ultimately a matter of chemical interactions.
 - B. By the next decade, proteins were being promoted as the key to cell processes, and geneticists were identifying genes with the production and action of proteins. The idea that proteins had a fixed structure was established only with the acceptance of Staudinger's macromolecule theory.
 - 1. Proteins, however, work in the body of the cell, not the nucleus, and genes were associated with chromosomes, which are in the nucleus. The relationship between proteins and genetics was unclear throughout the 1920s–1930s.
 - 2. In the 1860s, Friedrich Miescher claimed a role in heredity for nucleic acids. In the 1930s, DNA was identified, but it was dismissed as uninteresting, because it seemed to be merely a mix of four different types of bases.
 - 3. DNA was set aside in favor of the theory of George Beadle and Edward Tatum that genes make enzymes and enzymes do the work in the cell. This *one-gene/one-enzyme theory* linked biology and biochemistry, but it was wrong.
 - 4. In 1944, Oswald Avery and collaborators established DNA in the nucleus of the cell as the carrier of inheritance.
 - C. Between 1925 and the late 1940s, a number of technical developments in biology and chemistry played critical roles in enabling the discovery of the structure of DNA in 1953. As we have seen, the instruments that are available to science have a profound influence on the theories that are formulated.
 - 1. In the 1920s, scientists had reached a consensus that large molecules had a precise chemical and spatial structure. At that time, X-ray crystallography became available and was in use by physicists to study the structure of crystals.
 - 2. By the early 1950s, biologists learned how to crystallize biological molecules without warping them, which enabled the use of X-ray crystallography to study the structures of these molecules.

3. In 1950–1951, Linus Pauling used this technique to study proteins and discovered that all proteins have the same structure, which he called an *alpha helix*.
4. In 1953, Pauling and, independently, Watson and Crick used X-ray crystallography to study DNA. Of course, Watson and Crick were the first to announce the double-helix structure of the molecule that is central to genetics.
5. Four years later, Mathew Meselson and Frank Stahl showed that DNA reproduces when the two helices separate and each creates a complementary helix. From that point on, the dominant model in biology was that genes were carried by DNA.

Essential Reading:

Frederic L. Holmes, *Meselson, Stahl and the Replication of DNA: A History of "The Most Beautiful Experiment in Biology."*

William Provine, *The Origins of Theoretical Population Genetics.*

James D. Watson, *The Double Helix: A Personal Account of the Discovery of the Structure of DNA.*

Supplementary Reading:

Garland Allen, *Life Science in the Twentieth Century.*

Questions to Consider:

1. Do genes *determine* what we are, let alone who we are?
2. After 100 years of Mendelianism, is *gene* the name of a specific molecular thing or of a specific function physically distributed across the DNA molecule and even beyond it?
3. How can structure be so important in determining function, not only in physics and chemistry but also in biology? Is it as important at the level of society, as well?

* *Clarification:* Bateson called for the public adoption of the term *genetics* to describe discrete inheritance theory in 1905, but used the term privately earlier. He and others quickly adopted the term *gene* from 1909 on, but it seems first to have been used by Wilhelm Johannsen at a lecture at Columbia University that year.

Biographical Notes

Alvarez, Luis Walter (1911–1988): American physicist; created an artificial mercury isotope whose emitted light wavelength became the basis for the U.S. standard of length; discovered tritium; developed new types of radar during the war; built the first linear accelerator for protons, discovering scores of “elementary” particles; proposed the asteroid/comet collision theory to explain the mass extinction at the end of the Cretaceous (65 million years ago).

Bacon, Francis (1561–1626): British jurist, educational reformer, and philosopher who articulated a rigorously empirical-inductive method for identifying the covert causes responsible for natural phenomena.

Beard, Charles (1874–1958): American historian; his 1913 history of the writing of the American Constitution, which emphasized the economic motives of the Founders of the Republic, not their political ideals, was the opening salvo in his lifelong war against objectivist history-writing.

Berg, Paul (1926–): American biochemist; developed the basic techniques of recombinant DNA and organized the 1975 Asilomar Conference, at which researchers debated the ethics and hazards of genetic engineering and defined research safety standards.

Bethe, Hans (1906–): German-American physicist, a major contributor to nuclear physics, quantum physics, the fusion theory of stellar energy, and the life cycle of stars; after World War II, he was active in attempts to limit the possibility of nuclear war.

Bohr, Niels (1885–1962): Danish physicist; with Einstein, the leading architect of the “old” (1905–1925) quantum theory of matter and energy and the leading philosopher-interpreter of quantum mechanics in its formative years (1925–1935); with Heisenberg, creator of the Copenhagen interpretation of quantum mechanics as a fundamentally probabilistic theory describing experience, not an independently existing reality.

Bush, Vannevar (1890–1974): American engineer-scientist, architect of America’s post-World War II policy of public support for scientific research as the seedbed of technological innovation. Pioneer of mechanical analog computers in the 1920s and 1930s, he served as president of the Carnegie Institution, then as head of the Organization of Scientific Research and Development throughout World War II.

Chomsky, Noam (1928–): American linguist; the most influential linguist of the second half of the century, dismissing all earlier theories of language in favor of his view that language is a fundamentally neuro-anatomical phenomenon, hence, universal in its “deep structure.”

Crick, Francis (1916–): British physicist-turned-molecular-biologist after World War II who, with James Watson, discovered the double-helical structure

of the DNA molecule in 1953. In the 1960s, Crick played an important role in uncovering how the base sequences in the DNA molecule translate into instructions for protein synthesis, later focusing his research on neurobiology and a materialistic theory of consciousness.

De Broglie, Louis (1892–1987): French physicist whose 1923 doctoral dissertation extended early quantum theory by arguing that, just as waves behaved like particles, particles must behave like waves. His prediction was confirmed three years later.

Derrida, Jacques (1930–): French philosopher; Derrida dramatically extended de Saussure’s theory of language, developing the methodology called *deconstructionism*, which makes the determination of meaning an open-ended, dynamic phenomenon to be explored by way of networks of relationships that are the sole source of meaning.

Dewey, John (1859–1952): American philosopher, educator, and social reformer; known for developing into a comprehensive system the philosophy called *pragmatism* introduced by Charles Sanders Pierce in the 1870s and championed by William James.

Dirac, P.A.M. (1902–1984): British electrical-engineer-turned-physicist, creator of the relativistic theory of the electron, and the founder of what became quantum electrodynamics. His prediction of the positron was a startling instance of the fertility of abstract mathematics for revealing physical reality.

Domagk, Gerhard (1895–1964): German chemist; in the mid-1930s, he created the first synthetic antibiotic, Prontosil, and subsequently, the family of drugs called sulfonamides, based on the chemistry of synthetic dyes.

Durkheim, Emile (1858–1917): French sociologist, the founder of modern sociology and of a relational theory of society and of the “forces” that a society exerts on its members.

Einstein, Albert (1879–1955): German-born physicist, creator of the special and general theories of relativity, and arguably, the founder of quantum physics.

Fermi, Enrico (1901–1954): Italian physicist; he played a central role in nuclear physics in the 1930s, especially the physics of fission, and in 1942, as a prelude to the Manhattan Project, built the first nuclear reactor as a demonstration that the abstract physics actually worked.

Feynman, Richard (1918–1988): American physicist; with Julian Schwinger and the Japanese physicist Sin-Itiro-Tomonaga, founder of quantum electrodynamics; influential teacher and author of an irreverent autobiography.

Fischer, Emil (1852–1919): German chemist; a major contributor to turn-of-the-century organic chemistry, especially the detailed structure and synthesis of complex sugars, Fischer pioneered the study of enzymes, establishing the number of amino acids used by the human body to build proteins and the

relationships among the amino acids and successfully synthesizing peptides (protein-like amino acid chains).

Foucault, Michel (1926–1984): French philosopher, one-time mentor-collaborator of Derrida, flamboyant critic of cultural orthodoxy, and author of very influential histories of Western cultural institutions that exposed their underlying logics of power.

Fowler, William (1911–1995): American physicist; with Fred Hoyle and Geoffrey and Margaret Burbidge, explained how all the elements could be synthesized by stars, then disseminated into interstellar space when stars ended their lives explosively.

Frege, Gottlob (1848–1925): German mathematician; almost single-handedly founded modern mathematical logic and, through his interpretation of concepts, launched a fundamental reorientation of 20th-century philosophy.

Friedman, Milton (1912–): American economist; opponent of Keynesian economics in favor of his own monetarist economic theory based on money-flow models.

Freud, Sigmund (1856–1939): Austrian psychologist; founder of psychoanalysis as a methodology, of the unconscious as the dominant factor in human behavior, and of the sexual trauma theory of neurosis/psychosis; creator of the theory of repression, the Oedipus complex, and the Ego-Id/Libido-Superego model of the mind.

Gamow, George (1904–1968): Russian-American physicist; best known for his Big Bang theory of the origin of the universe and prediction of the microwave background radiation. He made important contributions to 1930s quantum physics, including predicting the quantum tunneling phenomenon, and informed Watson and Crick how the sequence of bases in their DNA molecule could “code” for the synthesis of proteins out of amino acids.

Geertz, Clifford (1923–): American cultural anthropologist; initially an objectivist, Geertz became a leading expositor of the view that a culture was a symbol system, the meaning of whose material remains could not be understood without understanding the underlying symbols of that culture.

Gell-Mann, Murray (1929–): American physicist; he formulated the *Eightfold Way* of organizing the hundreds of so-called elementary particles known by 1960 into families and, concurrently with George Zweig, created the quark theory of matter, which he called *quantum chromodynamics*.

Gödel, Kurt (1906–1978): Austrian mathematician and mathematical logician; his proof that Hilbert’s requirement that mathematics be consistent and complete could not be met was an intellectual tour de force that also led to Turing’s follow-on proof of the unsolvability of another of Hilbert’s problems, which led to the first computers.

Guth, Alan (1947–): American physicist; founder of inflation theory, which made the universe unimaginably vast and the result of a quantum vacuum fluctuation phenomenon.

Hale, George Ellery (1868–1938): American astronomer; eminent solar astronomer but best known for his tireless promotion of private support for scientific research—resulting in the Yerkes, Wilson, and Palomar Observatories, each housing in its time the world’s largest telescope—and of organizing academic scientists as a national resource in peacetime, as well as in war.

Hawking, Stephen (1942–): British physicist; best known as a theoretician of space, time, gravity, and black holes; his work, along with that of Jakob Bekenstein, which Hawking initially rejected, is fundamental to the search for a quantum theory of gravity.

Heisenberg, Werner (1901–1976): German physicist; one of the giants of quantum physics through his 1925 formulation of matrix mechanics and his collaboration with Bohr on the physical meaning of quantum mechanical theory, especially the Uncertainty Relations/Principle of 1927 and the 1929 Copenhagen interpretation of quantum mechanics.

Hilbert, David (1862–1943): German mathematician and philosopher of mathematics; eminent as a mathematician and founder of the formalist interpretation of mathematics, Hilbert is best known for his 1900 and 1929 challenges to the world’s mathematicians to solve a series of problems he formulated. The solutions have proven to be enormously fertile, scientifically, technologically, and mathematically.

Hoyle, Fred (1915–2001): British astrophysicist; best known for dismissively rejecting what he called the Big Bang theory of the origin of the universe in favor of his own Steady State theory, in which there is no origin and no end. With William Fowler and the Burbidges, worked out how stars could synthesize all the natural elements.

Hubble, Edwin (1889–1953): American astronomer; Hubble discovered that there were other galaxies besides the Milky Way and that galaxies were all moving away from the Earth as if the universe as a whole were expanding; he developed the first techniques for estimating the age and size of the universe.

James, William (1842–1910): American psychologist and philosopher, early proponent of experimental psychology, author of a text that remained influential for decades, and a champion of pragmatism.

Jung, Carl (1875–1961): Swiss psychologist; noted for his anti-Freudian approach to psychoanalysis based on his theory of the collective unconscious.

Kahneman, Daniel (1934–): Israeli-American social scientist; with Amos Tversky, built a compelling empirical case for the non-rational character of human decision-making with major implications for philosophy, psychology,

and social science generally, but rational choice theory–based economic models in particular.

Keynes, John Maynard (1883–1946): British economist; perhaps the single most influential economic theorist of the century in terms of government policy.

Kuhn, Thomas (1922–1996): American historian of physical science; his 1962 *Structure of Scientific Revolutions* triggered a relativism-based critique of objectivity that transformed history, philosophy, and sociology of science, in part, causing the Science Wars of the 1980s and 1990s.

Lawrence, Ernst O. (1901–1958): American physicist; from the day he arrived at Berkeley in 1930, his focus was on building ever-more-powerful cyclotron-style charged-particle accelerators that exploited the resonance principle as tools for atomic physics research.

Leakey, Louis (1903–1972): Kenya-born British paleoanthropologist; with his wife, Mary, and later, his son Richard, Leakey transformed our understanding of human evolution through his fossil discoveries in east Africa, especially Olduvai Gorge, laying the foundation for the *Out-of-Africa theory* of humanity.

Lévi-Strauss, Claude (1908–): French anthropologist; founder of structuralism, which in the 1960s and 1970s, was broadly adopted as a methodology by social scientists and literary theorists.

Maxwell, James Clerk (1831–1879): Scots physicist; founder of classical electromagnetic theory and electrodynamics, simultaneously the basis for quantum electrodynamics and superseded by quantum chromodynamics.

Mead, George Herbert (1863–1931): American sociologist; founder of social behaviorism, an interactional-relational theory of the self and of society with pragmatist overtones.

Minsky, Marvin (1927–): American computer scientist; one of the founders of artificial intelligence research, creator of MIT's AI Laboratory, and champion of the view that thinking is calculating with symbols, thus, a strong opponent of neural net models.

Oppenheimer, J. Robert (1904–1967): American physicist; Oppenheimer is best known for having been the director of the Manhattan Project and for the loss of his security clearance for having opposed developing the hydrogen bomb, but in the 1930s, he was an important contributor to quantum theory.

Pareto, Vilfredo (1848–1923): Italian sociologist and economist whose theories of society and the economy, based not on objective reason but emotion and will, were taken up in the 1930s and became central to one strand of modern economic, and welfare state, theory.

Pauli, Wolfgang (1900–1958): Austrian physicist; his 1924 Exclusion Principle provided the first systematic explanation of the periodic table and opened the

way to Schrödinger's and Heisenberg's versions of quantum mechanics. Pauli also solved the problem of beta decay in 1930 and predicted the existence of what became known as the neutrino.

Pauling, Linus (1901–1994): American chemist; formulated the definitive theory of chemical bonding in his 1940 text employing quantum physics to explain inter-atomic bonds and new physics-based technologies, including X-ray crystallography to determine the molecular structure of biochemical molecules, thus paving the way for Watson and Crick.

Prigogine, Ilya (1917–2003): Belgian chemist; championed the study of irreversible processes, self-organizing systems, nonequilibrium thermodynamics, and nonlinear dynamics, enriching our understanding of entropy and laying the foundation for the study of complex systems.

Russell, Bertrand (1872–1970): English mathematician, mathematical logician, and philosopher; Russell demolished Frege's project to reduce arithmetic-based mathematics to logic, then collaborated with Alfred North Whitehead on an attempt at reducing all of mathematics to logic.

Rutherford, Ernst (1871–1937): New Zealand-born British physicist; Rutherford's Cambridge University laboratory was, for decades, a remarkably fertile source of important experimental and theoretical developments. Rutherford formulated the modern, so-called solar system model of the atom, which stimulated Bohr to propose a quantum theory of orbital electrons that launched quantum physics and chemistry.

Samuelson, Paul (1915–): American economist; perhaps the greatest influence on the adoption of sophisticated mathematical analysis by post-World War II economists and an architect of dynamic economic theory.

Sanger, Frederick (1918–): English biochemist, received two Nobel Prizes for chemistry (1958 and 1980) for having determined the complete molecular structure of insulin and for working out the basic techniques for determining the sequence of bases in DNA.

Saussure, Ferdinand de (1857–1913): Swiss linguist; best known for his very influential theory of language as a closed system of relationships.

Schrödinger, Ernst (1887–1961): Austrian physicist; one of the giants of quantum mechanics, especially in the period 1924–1934. His wave mechanics of 1925 became the basis of Dirac's relativistic theory of the electron, which evolved into quantum electrodynamics.

Shannon, Claude (1917–2001): American mathematician; with Warren Weaver, he laid the foundation for modern communication and information theory, which became important resources for the new fields of systems analysis and computer science.

Simon, Herbert (1916–2001): American social scientist but not an economist by training, Simon received the Nobel Memorial Award in Economics for his studies of organizational decision-making, emphasizing the concepts of *bounded rationality* and *satisficing*. With Alan Newell, he was, in the 1960s, a pioneer of artificial intelligence research.

Skinner, B. F. (1904–1990): American psychologist; in the 1930s, Skinner revived John Watson's crude stimulus-response behaviorism and made reinforcement-based behavioral psychology the dominant paradigm until the rise of cognitive psychology in the 1970s.

Turing, Alan (1912–1954): English mathematician; his 1936 proof that, contrary to Hilbert's challenge, there could be no mechanical decision procedure in mathematics led to the conceptual design of the modern computer.

Von Neumann, John (1903–1957): Hungarian-American mathematician of enormous influence in mathematics, physical science, computer science, and social science. Founder of game theory, established the basic software and hardware architectures for stored-program electronic computers, pioneer of the theory of automata, and an important contributor to set theory and quantum mechanics.

Watson, James (1928–): American biochemist; received his Ph.D. at age 22 and, shortly thereafter, with Francis Crick, discovered the double-helix structure of DNA, launching molecular biology.

Weber, Max (1864–1920): German sociologist; best known for arguing that the roots of capitalism lie in the Protestant ethic and that the human and social sciences necessarily require an interpretive, rather than an inductive or deductive, method.

Wegener, Alfred (1880–1930): German meteorologist and geologist who, in 1915, proposed a theory of continental drift that, after initial ridicule, evolved into plate tectonics.

Wheeler, John (1911–): American physicist; with Gamow and Oppenheimer, one of the most eminent physicists of the century not to have been awarded a Nobel Prize. Wheeler made major contributions to gravitation theory and coined the name *black hole*.

Wiener, Norbert (1894–1964): American mathematician and scientist, founder of cybernetics, pioneer of mathematical modeling of mechanical and biological systems, and an important contributor to information theory and system theory.

**Science in the Twentieth
Century:
A Social-Intellectual Survey
Part III
Professor Steven L. Goldman**



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Steven Goldman has degrees in physics (B.Sc., Polytechnic University of New York) and philosophy (M.A., Ph.D., Boston University) and, since 1977, has been the Andrew W. Mellon Distinguished Professor in the Humanities at Lehigh University. He has a joint appointment in the departments of philosophy and history because his teaching and research focus on the history, philosophy, and social relations of modern science and technology. Professor Goldman came to Lehigh from the philosophy department at the State College campus of Pennsylvania State University, where he was a co-founder of one of the first U.S. academic programs in science, technology, and society (STS) studies. For 11 years (1977–1988), he served as director of Lehigh's STS program and was a co-founder of the National Association of Science, Technology and Society Studies. Professor Goldman has received the Lindback Distinguished Teaching Award from Lehigh University and a Book-of-the-Year Award for a book he co-authored (another book was a finalist and translated into 10 languages). He has been a national lecturer for Sigma Xi—the scientific research society—and a national program consultant for the National Endowment for the Humanities. He has served as a board member or as editor/advisory editor for a number of professional organizations and journals and was a co-founder of Lehigh University Press and, for many years, co-editor of its Research in Technology Studies series.

Since the early 1960s, Professor Goldman has studied the historical development of the conceptual framework of modern science in relation to its Western cultural context, tracing its emergence from medieval and Renaissance approaches to the study of nature through its transformation in the 20th century. He has published numerous scholarly articles on his social-historical approach to medieval and Renaissance nature philosophy and to modern science from the 17th to the 20th centuries and has lectured on these subjects at conferences and universities across the United States, in Europe, and in Asia. In the late 1970s, the professor began a similar social-historical study of technology and technological innovation since the Industrial Revolution. In the 1980s, he published a series of articles on innovation as a socially driven process and on the role played in that process by the knowledge created by scientists and engineers. These articles led to participation in science and technology policy initiatives of the federal government, which in turn, led to extensive research and numerous article and book publications through the 1990s on emerging synergies that were transforming relationships among knowledge, innovation, and global commerce.

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Science in the Twentieth Century: A Social-Intellectual Survey

Scope:

In the course of the 20th century, the practice of science, professionally, intellectually, and in relation to society, increased in scope, scale, and complexity far beyond what had been anticipated at the end of the 19th century. All of the sciences became inextricably entangled with social, political, and commercial forces and values. From the perspective of society, at least, this erased the distinction between pure and applied science, between knowledge and its “fruits,” which had been passionately espoused by many leading 19th-century scientists. As scientists created increasingly powerful theories, people—often scientists themselves—applied those theories to develop technologies whose exploitation created new wealth, new forms of power and control, new ways of life...and new dependencies on more science to create newer technologies!

Concurrently, the practice of science became increasingly formalized, institutionalized, and professionalized. This professionalization reflected and was driven both by the rise of a large number of people who made a living as scientists, in comparison with the comparatively modest community of mostly gentlemen scientists in the 19th century, and by the steadily increasing significance of science to society from the last third of the 19th century through the 20th century. Two hundred and fifty years after the pioneering work of Descartes, Francis Bacon, and Galileo, science suddenly mattered—not just to intellectuals, but to everyone and in profoundly existential ways.

Intellectually, too, the discoveries and theories of 20th-century physical, life, and social scientists exceeded anything that had been anticipated, even by the greatest of 19th-century scientists. As 1900 approached, leading physicists claimed that, apart from the details, the task of science was nearing completion; however, by the end of the 20th century, effectively every 19th-century theory of natural and social phenomena would be overthrown or superseded.

The first lecture in this course establishes its objective: to trace an intellectual history of the physical, life, and social sciences in the 20th century, organized around an evolving scientific understanding of matter and energy, the universe, Earth, life, and humanity, subsuming under the last category theories of culture, society, and mind.

Complementing this survey of a century of science from the “inside,” in terms of its ideas and discoveries, will be an account of the evolution of 20th-century science from the “outside,” that is, of its evolving relationship with society. It is this reciprocal relationship between science and society that makes an understanding of the sciences as a whole in the 20th century important, and not

simply as history, because science is implicated in all of our 21st-century prospects, the threats no less than the promises.

Lectures Two through Eleven describe our evolving understanding of matter and energy, the foundations of the physical and life sciences. We begin with the special and general theories of relativity and how they redefined what we mean by space, time, matter, energy, and motion: in short, what the framework of reality is for the physical sciences.

Given that quantum theory is the most important and intellectually revolutionary scientific theory of the 20th century, eight lectures are devoted to it. Lectures Three and Four trace the early history of the theory, from the tentative introduction of the quantum hypothesis in 1900 to the formulation of quantum mechanics in 1925 and its radical Copenhagen interpretation in 1929. Our goal is a qualitative appreciation of the innovative ideas underlying the theory and of the bizarre microworld underlying ordinary experience that it revealed. Lectures Five through Eight describe the creation and application of the second stage of quantum theory's development, quantum electrodynamics (QED), from 1929 to 1965. Lectures Nine and Ten describe the transition from QED to quantum chromodynamics (QCD) and the unification of all known fundamental forces of nature.

Lecture Eleven concludes the discussion of matter and energy by highlighting major events in the evolution of chemistry, emphasizing the transformation wrought by its assimilation of quantum theory and its growing power to create molecules by design.

The obscurity of the theories of 20th-century physical science from the perspective of the non-scientist public is overwhelmingly a consequence of the forbidding mathematics that has become the language of science. Lectures Twelve and Thirteen discuss controversies in the first half of the 20th century over the relationship between mathematics and truth, and between mathematics and reality, as well as the astonishing fertility of abstract mathematics for the sciences, even if the source of that fertility is not understood.

What we mean by the *universe* has changed, from 1900 to 2000, far more dramatically than anything else in the history of science, more even than the change wrought by Copernicus. Today, the universe is unimaginably more vast than it was thought to be in 1900, and the stories of its origin, constitution, and fate, discussed in Lectures Fourteen through Sixteen, are beyond science fiction!

Lectures Seventeen through Nineteen focus on our knowledge of planet Earth, especially the shift from a geology of static continents to plate tectonic theory. We also discuss the growing recognition of the Earth as a complex system, integrating a dynamic, evolving, physical Earth with its biosphere, oceans, atmosphere, and external and internal magnetic fields, the whole interacting with the solar system in general and the Sun in particular.

Lectures Twenty and Twenty-One address the “outside” of science, especially the rise of techno-science (science-based technology) and its connections to government, industry, and society.

Lectures Twenty-Two through Twenty-Six address our understanding of life, treating the history of evolutionary biology, human evolution, genetics, molecular biology, and science-based medicine.

Lectures Twenty-Seven through Thirty-Four focus on our knowledge of humanity. This group includes three lectures on the evolution of anthropological theories of human culture, the field and theoretical work of archaeologists, important developments in linguistic theory, and changing conceptions of history as a science. Three lectures describe theories of society, the state, and economies, theories that have had profound implications for national and global political agendas and actions in the course of the 20th century. Two lectures describe changing theories of the human mind, our most intimate attempt at self-understanding, from the enormously influential theories of the unconscious by Freud and Jung early in the century, through the equally influential behavioral psychology that dominated the mid-century, to the cognitive psychology that came to the fore in the late century, especially cognitive neuroscience allied to artificial intelligence research.

Lectures Thirty-Five and Thirty-Six review the major concepts of 20th-century science and discuss their broader cultural and intellectual significance, survey the leading edges of the sciences at the close of the 20th century, and look ahead to the continuing evolution of science in the 21st century.

Lecture Twenty-Five

Molecular Biology

Scope: There is more to life than genetics! The atomic theory of matter had become a dogma of science only in the second decade of the 20th century, but already, the course of biological research had shifted from the study of organs and organisms to the study of the chemical and, ultimately, molecular bases of metabolic processes. This brought into biology, first, chemists and, from the late 1930s, people trained as physicists. With the new people came new approaches to identifying and solving biological problems. The assimilation of biophysics and biochemistry was reflected in the centrality to research programs of identifying fundamental “elements” of cellular processes and discovering their chemical compositions and atomic structures. Initially, the focus was on enzymes, but by the end of the century, the success of these programs, evidenced by the DNA story, brought information theory into biology in the form of bioinformatics and highlighted *proteomics*, discovering the complex folded structures of proteins, as the key to understanding life.

Outline

- I. By the end of the 20th century, molecular biology was the dominant focus of life science research.
 - A. The term *molecular biology* was used in 1938 by Rockefeller Foundation President Warren Weaver. Molecular biology is an expression of the steady growth of biochemistry and physical chemistry in explaining metabolic processes.
 1. The term *biology* was coined in the early 19th century to identify a discipline for studying the special phenomena associated with life. A generic term for the force that was distinctly associated with life was *vitalism*, or *élan vitale*.
 2. In this sense, biology in the early 1800s was out of step with the rest of physical science, which was materialistic, deterministic, and mechanistic.
 3. Hence, there was a strong push to interpret the vital force physically, chemically, and mechanistically. For this reason, in the course of the 19th century, chemistry and biology became intertwined.
 4. Biology, however, was still interested in the processes of life, which typically brought the focus to the level of organisms and organs.

5. The molecular approach focuses quite narrowly on molecular processes and on structure as a determinant of physiological processes.
 6. As we shall see, it was in biology that *reductionism* first manifested itself, that is, the reduction of life phenomena to nonliving physical and chemical phenomena and, ultimately, to structural relationships among forces and particles.
- B.** The debate between reductionism and vitalism continued from the 1850s to the end of the 19th century, but by 1938, reductionism seemed to have won. How did biologists move from studying organisms, organs, and physiological processes to molecular processes?
1. Ivan Pavlov, in 1902, began his studies of conditioned reflexes that, in the 1920s, became a long-term research program in the physiology of behavior. In principle, all human behavior was seen as a manifestation of complex conditioned reflexes. This view was one step toward a mechanistic interpretation of life, and it was influenced by many other steps in that direction in the first few decades of the 20th century.
 2. Jacques Loeb, first, in Germany, then, in the United States, championed a mechanist view of life, supported by his research on tropisms and artificial fertilization. His 1912 book *The Mechanistic Conception of Life* was very influential.
 3. Concurrently, scientists were finding mechanistic reductions of animal behavior that were translated into human behavior. In 1911, Edward Thorndike published *Animal Intelligence*, which together with Pavlov's work on conditioned reflexes, led John Watson to publish his text on behaviorism in 1913. This view holds that human beings don't act; they react to external stimuli.
- C.** Increasingly sophisticated physiological studies also enabled plausible arguments for the "machine-like" character of human beings.
1. Charles S. Sherrington in England, for example, exposed the detailed neurophysiology of the reflex arc and identified inhibition as a critical factor in muscular action.
 2. In the United States, L. J. Henderson and Walter B. Cannon, colleagues at Harvard Medical School, added complementary studies that advanced a physical interpretation of life: Henderson, of internal self-control mechanisms in mammals, which he modeled mathematically, for example, in his 1921–1931 lectures on blood; Cannon, on the action of the sympathetic nervous system, coining the term *homeostasis* to describe the means by which bodily processes act to sustain "dynamic equilibrium."
- D.** Between 1900 and the 1930s, then, there was a growing body of scientific work supporting the view that, ultimately, all human

behavior—both physiological and psychological—can be explained by physical and chemical processes.

- E. At the same time, in chemistry, there was a growing emphasis on structure as the key to chemical properties.
 - 1. By the end of the 1920s, most biologists agreed that biological molecules are long molecules with precise structures and shapes.
 - 2. One of the great 19th-century discoveries was the importance of spatial arrangement to the chemical and physical properties of molecules.
 - 3. The combination of reductionism in biology with the focus on structure in chemistry gave birth to molecular biology.
 - 4. The next logical step was to reduce biology to the study of the structure of molecules in order to understand life processes.
 - F. Let's look at one concrete example of the reduction of life processes to structure.
 - 1. In 1949, Linus Pauling, who had, since 1940, called for a molecular description of the antigen-antibody reaction and would, in 1951, identify the alpha-helix structure of proteins, gave a molecular account of sickle cell anemia.
 - 2. The victim's hemoglobin had an anomalous electric charge, caused by a single amino acid error in one protein, that warped the cell's shape so that it could not flow through narrow blood vessels.
- II. Molecular biology has been described as having three "strands."
- A. The chemical and the structural are two of these strands, and the third is information, which emerged in the 1950s and reflected a second wave of physicists taking an interest in biology. This manifested itself strongly in the case of Watson and Crick and the interpretation of DNA.
 - B. The 1948 book *Cybernetics* by Norbert Wiener described apparently purposeful behavior displayed by machines, attributed to self-control mechanisms based on feedback loops. In the same year, Claude Shannon and Warren Weaver published the foundational paper in modern information theory.
 - C. By the end of the 1940s and early 1950s, physics was focused on information as a principle of reality, analogous to structure.
 - D. Watson and Crick's discovery of the structure of DNA prompted the question: What does DNA do?
 - 1. George Gamow noticed a peculiar correlation between the number of combinations of the 4 DNA bases and the number of amino acids used to make proteins. Could there be a functional connection between the base sequences and the amino acids?

2. Crick and others in the 1960s–1970s worked out the DNA base sequence “code,” confirming Gamow’s idea that DNA is an information structure, a code book for manufacturing proteins.
- E. Recall that in the early 1900s, the gene was conceived as analogous to the atom in chemistry and physics. The work of Jacques Monod and François Jacob revealed that genes act through networks, not individually.
1. The network of genes triggers the manufacture of certain proteins at certain times and for particular cells.
 2. In fact, at the end of the 20th century, scientists were questioning the existence of individual entities called *genes*.
- F. To say that DNA is an information structure seems unsatisfying on some level. DNA is the code for making proteins, and proteins trigger certain cellular processes, but does this fact answer the question: What is life?
- G. At the end of the 20th century, we see a severe disconnect between genetics at the level of molecular biology and the classic concern of biology. What sense can we make of the revelation that life is an information structure?

Essential Reading:

Michel Morange, *A History of Molecular Biology*.

———, *The Misunderstood Gene*.

Supplementary Reading:

James D. Watson, *DNA: The Secret of Life*.

Questions to Consider:

1. How strong is the case for reductionism? Is it more or less threatening than the idea of evolution to traditional conceptions of the meaning of life?
2. What are the implications for our understanding of life and reality of interpreting the DNA molecule as a carrier of information?
3. Why do we persist in positing “atomic” mechanisms for new natural phenomena even after the shift to process and relational models in explaining other phenomena?

Lecture Twenty-Six

Molecular Medicine

Scope: Like mathematics, though for different reasons, medicine is not, strictly speaking, a science, and the history just of 20th-century medicine demands a course of its own. Nevertheless, the essence of 20th-century medicine, as of 20th-century technology generally, surely is its science-based character. Furthermore, the theories, concepts, and diagnostic and therapeutic tools that were a driving force in the evolution of 20th-century medicine echoed parallel developments in biology. The development of serums and vaccines, theories of disease and models of the ways they spread; the use of X-rays, fluoroscopy, CAT scans, and magnetic resonance imaging; the embrace of genomics and the pursuit of genetic engineering—all are illustrative of the assimilation into medicine of physics- and chemistry-derived influences.

Outline

- I. Medicine in the 20th century reflects the same influences from physics and chemistry that were at work in research biology.
 - A. Twentieth-century medicine is associated with dramatic changes in the lifestyle of the public in developed countries. For example, the life expectancy in the United States in 1900 was 47 years and a few months; today, it is in the high 70s.
 - B. The speed with which Watson and Crick's abstract and fundamental work in molecular biology has entered the mainstream of medical practice is phenomenal.
 1. Just four years after the discovery of the structure of DNA, Arthur Kornberg identified the enzyme responsible for bonding the base pairs of DNA.
 2. In 1972, Paul Berg performed the first successful recombinant DNA experiment, and over the next five years, techniques were developed for disassembling DNA at will. Berg became concerned about the ethics of recombinant DNA technology and prompted the establishment of safety procedures for labs involved in DNA research.
 3. In 1977, bacteria were used to synthesize human somatostatin. In 1980, the human interferon-producing gene was inserted into a bacterium for mass production, and in 1982, the FDA approved genetically engineered human insulin produced by bacteria.
 4. In 1980, the first transgenic plants and animals were created, and the possibilities for commercialization of this technology were recognized.

5. In 1983, the first monoclonal antibody was approved for a diagnostic test, suggesting that medicine might be able to produce unlimited quantities of highly specific antibodies to fight disease. In 1985, recombinant DNA technology was used to produce Human Growth Hormone commercially, and in 1986, the first antibody-enzyme hybrids were created, launching a new class of pharmaceuticals.
 6. In 1997, the first artificial human chromosome was created, suggesting the potential of molecular biology to provide increasingly powerful therapeutic tools.
- C. Twentieth-century medicine also saw the development of molecular psychiatry, that is, the reduction of mental processes to the structure of molecular processes. Examples include study of the relationship between the serotonin-producing gene and suicidal behavior and between the serotonin transport gene and depression as a response to stress; between proteins and anorexia; and between the neuregulin-1 gene and schizophrenia.
- II. The history of the pharmaceutical industry and of medical imaging technologies reveals other dimensions of the extent to which the evolution of 20th-century medicine has been driven by its assimilation of molecular biology.
- A. An illuminating historical case study looked at the evolution of one turn-of-the-20th-century company, Philadelphia-based H.K. Mulford, which produced and marketed bacterial vaccines and vaccine-use kits, along with serum anti-toxins, which added up to a “high-tech” product line for the day.
1. Mulford sought help from an entrepreneurial fellow graduate of the Philadelphia College of Pharmacy, hired academic researchers as consultants, and adopted a marketing strategy based on product innovation, research on dosage standardization, a reputation for quality, and accompanying documentation.
 2. The company thrived until the mid-1920s when innovation flagged, and in 1929, Baltimore ethical drug distributors Sharp and Dohm bought Mulford to gain access to the biologicals market.
 3. Sharp and Dohm invested heavily in research and production innovation in the mid- to late 1930s, manufacturing sulfa drugs, followed by penicillin and streptomycin. In the process, they dropped effective polyvalent bacterial vaccines because of the public fascination with antibiotics, then developed blood products, for which World War II provided a massive market. (Their process of dehydration and rapid freezing to preserve plasma became a major consumer food technology after the war.)
 4. In the 1950s, Sharp and Dohm research and product development shifted from antibiotics to viruses under both public and

government pressure to treat polio. In 1953, Merck, a supplier of fine chemicals and a manufacturer of synthetic vitamins, steroids, and antibiotics, merged with Sharp and Dohm in order to integrate vertically.

5. Merck moved aggressively into viral vaccine research and mass production of the poliovirus vaccine, in the 1970s shifting its research focus to molecular biology and DNA-based molecular genetics products. Bacterial vaccines were revived in the 1980s, this time using recombinant DNA technology, in which a virus is used as a gene delivery *vector*, or transmission mechanism.

- B. This case study represents just one example of how the pharmaceutical industry has moved in the direction of molecular therapeutic products.

III. Medical imaging technologies reveal a different route to molecular medicine.

- A. X-rays were the first medical-imaging devices.

1. Roentgen discovered X-rays in 1896, and by 1899, Edison was marketing fluoroscopes; by 1910, machines for medical and for dental practices were in production. But these were very crude machines, with exposure times measured in many minutes, and the causes of many injuries, especially to their operators.
2. William David Coolidge of MIT and General Electric's industrial research laboratory developed a much-improved X-ray tube that reduced exposures to seconds. World War I created a market for portable X-ray equipment and a demand for thousands of people trained to operate that equipment. Not incidentally perhaps, in the 1920s, chest X-rays became routine, in part sparked by tuberculosis fears.

- B. CAT scanners are a sophisticated enhancement of the X-ray phenomenon, although both technologies provide "outside-in" imaging.

1. In 1929, the idea was first broached for rotating an X-ray tube around a patient and creating a series of image slices that, in the late 1930s, was called *body-section roentgenography*. It was not until 1972 that the first commercial scanner was marketed by EMI of England, after which the technology developed very rapidly.
2. The underlying technology of CAT scans is based on a mathematical tool that has no relationship to medical imaging—*tomography*, a method for building two-dimensional images from one-dimensional data and three-dimensional images from two-dimensional data.

- C. The ultimate molecular medical-imaging devices are magnetic resonance imaging (MRI) and positron emission tomography (PET) scanners. These "inside-out" technologies allow us to image, not just bones and tissue, but processes in the body.

1. In 1939, Columbia University physicist I. I. Rabi measured the *magnetic moment* of the atomic nucleus, that is, the way in which the nucleus is magnetized. In 1952, the technique was adapted to measure atomic features of bulk matter, and it became an instant success in physics and chemistry research, with many industrial testing applications.
 2. The first NMR/MRI images (keyed to the nucleus of the hydrogen atom) of the human body came in 1981, and when superconducting magnets were adopted in 1986, the results were spectacular. Fast, so-called functional MRI machines in the 1990s allowed real-time imaging of brain processes, for example.
 3. In positron emission tomography, radioactive substances are injected into the body to build up an image of the organs in which the molecules of the tracers are contained.
- D. These technologies represent the spread of the mindset of the same ideas that were foundational to molecular biology.

Essential Reading:

Louis Galambos and J. E. Sewell, *Networks of Innovation: Vaccine Development at Merck, Sharp and Dohme, and Mulford, 1895–1995*.

Bettyann Kevles, *Naked to the Bone: Medical Imaging in the Twentieth Century*.

Paul Rabinow, *Making PCR: A Story of Biotechnology*.

Questions to Consider:

1. How can patients be re-integrated given the powerful dis-integrating tendencies underlying scientific and, especially, molecular medicine?
2. Is there a disconnect between medical definitions of health and commonsense conceptions of well-being?
3. Is there a threat to our humanness in molecular medicine even as its power to heal grows?

Lecture Twenty-Seven

Culture—Anthropology and Archaeology

Scope: The study of how non-European, especially non-literate, peoples lived was initiated as a science in the 19th century. Anthropologists spread out around the world, as naturalists had been doing for centuries, collecting interesting human “specimens,” identifying their distinctive behaviors, photographing them, classifying them. By the early 20th century, anthropology was an established science, but there was still unease over what its object was and what its methodology ought to be. If the object is “culture,” what exactly is that? Is the goal simply collecting lifestyle data and reporting them or discovering underlying patterns and themes common to all cultures? Is European culture “privileged,” a basis for making cross-cultural value judgments, or must the values of all cultures be accepted as valid in context? Is there a universal human nature that is expressed in many different ways, or is that a European myth, in which case, cultural diversity is an irreducible fact? Concurrently, archaeology went through a parallel development. It, too, began in the 19th century but flowered in the 20th, evolving from collecting and dating to reconstructing lifestyles and bringing physics, chemistry, geology, and biology to bear on this interpretive process. The result of 100 years of scientific anthropology and archaeology has been a more sophisticated and much more complex picture of human being than existed in 1900.

Outline

- I.** We now turn, in our intellectual odyssey, to the major ideas in the social sciences, ranging from anthropology, through linguistics, to psychology and the cognitive sciences.
 - A.** Along with the physical sciences, the social sciences are also part of the cultural phenomenon of science in the 20th century and have had profound implications for society, analogous to the impact of the physical sciences.
 - B.** Surprisingly, there are also analogies between the conceptual structures of the social sciences and the physical sciences. Certain basal ideas, including the reality of relationships and the power of structures, cut across disciplines.
- II.** The human sciences, or the social sciences, may seem “unscientific” in comparison to the hard sciences, because they seem to violate the fact-value dichotomy that is a fundamental principle of modern science.

- A. The subject matter of the human sciences explicitly incorporates value judgments, by contrast with the physical and life sciences, whose subject matters are value free.
 - 1. This poses a serious methodological problem for modern science, which insists on an absolute distinction between facts and values.
 - 2. This also raises the question of whether it is even possible for value-laden matters to be studied scientifically. In late-19th-century Germany, a distinction was drawn between *Naturwissenschaft* (“natural systemic knowledge,” namely, hard science) and *Geisteswissenschaft* (“human science”) in order to sustain a scientific status for the study of humanity.
 - B. Conceptually, anthropology precedes the other human/social sciences, though effectively, all of the others are older chronologically.
 - 1. The core concerns of anthropology all revolve around the question: What does it mean to be human? We might also ask: How can we study this question scientifically?
 - 2. The empirical methodology of anthropology, that is, the collection of information about how people live, does not seem to constitute a science, because it does not have explanatory power.
 - 3. Developmental sequencing is a way of converting a collection methodology into an explanatory methodology.
 - 4. Early in the history of anthropology, culture became the primary focus of study.
 - C. The next logical questions were: What is the methodology for studying culture and what is *culture*?
 - 1. Is there such a thing as *culture*, or like the terms *species* or *style* (in art), is *culture* a convenient name for an aggregate of practices? Can a culture exert forces/influences on its members? Do cultures develop over time in lawful ways, by deliberate choice, or haphazardly?
 - 2. Two giants of early-20th-century British anthropology, Bronislaw Malinowski and A. R. Radcliffe-Brown, took a functional approach to these questions from opposing perspectives: Malinowski, taking a people’s practices and institutions as ways of responding to individuals’ biological, psychological, and sociological needs; Radcliffe-Brown, beginning with social practices and how they shaped individuals in their image.
 - 3. Meanwhile, German anthropology was primarily ethnological, studying practices and the detailed forms they took, and American anthropology was primarily cultural.
- III. In anthropology, as in the social sciences generally, American influence rapidly became dominant.
- A. A German immigrant to America, Franz Boas, was a major influence on all of the social sciences in the first half of the century. Boas was a

relativist, rejecting the claim that all cultures evolved according to a single law and insisting on the integrity of all cultures and the need to understand each in context.

1. Boas's students, among them, Ruth Benedict (*Patterns of Culture*) and Margaret Mead (*Coming of Age in Samoa*), created a powerful culturally relativist anthropological school centered on the relationship of culture and personality.
 2. This school was interested in understanding how personality reflected the internalization by individuals of their cultures, including modern cultures (which brought anthropology and sociology together). Some members rejected anything resembling a Freudian unconscious; others (Abram Kardiner, for one) proposed a "hidden self" not defined by cultural experience.
 3. This empirical, relativistic approach characterized American anthropology in the period 1920–1950.
- B.** The mid-century saw a turn to a "harder" approach to anthropology.
1. In the 1950s, Leslie White and Julian Steward argued that cultures were materialistic systems, "elaborate thermodynamic systems" in one White metaphor, each possessing an inner structure whose development followed a deterministic order. In their view, cultures determined the behavior of their members; they were not the result of behavioral choices.
 2. Followers of White and Steward dismissed the Boas-inspired culture-and-personality school as unscientific and engaged in "ecological anthropological" studies, reflecting a systems interpretation of culture.
 3. In the 1960s, a structuralist approach to cultures, championed by Claude Levi-Strauss and adopted enthusiastically by social scientists and literary theorists, extended the systems interpretation, making cultures into networks of relationships.
- C.** The popularity of structuralism peaked in the 1970s. In its wake, anthropology splintered.
1. Prominent early followers of White and Steward, especially Marshall Sahlins and Clifford Geertz, broke with an impersonal, materialistic interpretation of culture. They argued that a culture could be understood only as a system of symbols whose meanings in the minds of members determined the culture's unity and character. This "humanistic," as opposed to naturalistic, approach to anthropology was embraced in the 1980s and afterwards.
 2. Meanwhile, ecological anthropology, with its focus on adaptation, developed along multiple lines in the renewed attempt to apply hard-science concepts and methodologies to the study of culture.
 3. The naturalist-humanist division became sufficiently intense to splinter the American Anthropological Association, leading to the

creation, on the 100th anniversary of the association in 2002, of the Society for Scientific Anthropology!

- IV. Archaeology is, in effect, the material side of anthropology, and it, too, matured as a science in the 20th century, building on 19th-century beginnings.
- A. In the course of the century, archaeology went from digging up artifacts (analogous to the phase of documenting primitive peoples in anthropology) to reconstructing lifestyles. In the process, archaeologists developed methodologies for collecting artifacts that would allow for objective dating and comparison.
 - B. Understandably, given its European-Christian origin, early archaeology focused on biblical and classical themes and on recovering texts and “art” objects. This “natural history” approach to archaeology dominated the period from 1900 through the 1940s.
 - C. First in the 1940s and more rapidly after 1950, American archaeology shifted from collecting artifacts to explaining cultural development by way of material remains.
 - 1. Developmental sequencing entailed a more intensively technical approach to archaeology, involving instruments and expertise from geology, biology, chemistry, and physics. In turn, the interest in developmental sequencing led to increased interpretation and explanation. Between 1950 and 2000, archaeology moved in the direction of reconstructing lifestyles.
 - 2. The application of technology to archaeology has enabled more precise dating and location of artifacts, as it has raised new questions for anthropology.
 - D. In 1959, Joseph Caldwell issued a call for a “new American archaeology,” keyed to the concepts of ecology and adaptation. By the end of the 20th century, archaeology had become multidisciplinary, collaborative, and focused on cross-cultural interactions and drift as factors responsible for the complexity of societies and culture.

Essential Reading:

Clifford Geertz, *Interpretations of Cultures*.

Marshall Sahlins, *Culture and Practical Reason*.

Bruce Trigger, *A History of Archaeological Thought*.

Supplementary Reading:

Mathew Johnson, *Archaeological Theory: An Introduction*.

Questions to Consider:

- 1. Are facts and values fundamentally different from one another, and even if they are, why is the study of values so problematic for science?

2. Does cultural interaction imply homogenization, as in the great American “melting pot” metaphor?
3. Is the causal relationship between cultures and their members like the chicken-egg relationship?

Lecture Twenty-Eight

Culture—History

Scope: Is history a branch of the sciences or of the humanities? The legacy of the 19th century was that history, though often used for propagandistic storytelling, was in principle, a science. Early-20th-century historians thus pursued an objective methodology that would describe the way things *really* happened, free of conscious or unconscious ideology, bias, or subjective interpretation. Generations of graduate students were trained in techniques of evidence gathering that would allow them to get behind self-interest and partial perspectives. Between 1910 and 1930, however, a consensus began to grow that the past, distant or recent, is incapable of being “objectively” reconstructed. All history, in this view—including this survey of the sciences in the 20th century—is necessarily interpretive and, thus, a form of storytelling. Once this is recognized, the question arises as to what the principles of interpretation need to be to distinguish history writing from fiction. Stigmatized as a kind of cultural treason in the 1930s, relativism gave way to objective history, only to return in the 1960s, posing deeper challenges than before. Is history incapable of truth as the sciences understand truth? Is the plight of history as interpretation unique to history, or is interpretation, inevitably subjective or, at best, intersubjective, a problem not only for all of the social sciences but even for the so-called “hard” physical sciences?

Outline

- I. Is history “scientific”?
 - A. For Aristotle, history could not be a science because it lacked universality and necessity. The Renaissance humanist founders of modern history, however, put history at the heart of philosophy precisely *because* of its particularity and contingency!
 - B. In the 17th, 18th, and 19th centuries, the humanists were overcome by the modernists, who reintroduced rationalist philosophy in the guise of materialistic, deterministic science.
 - C. In the 19th century, history writing reflected the materialistic determinism of the sciences in general, and two models of history emerged.
 1. The first model goes back to the influential German philosopher Hegel, who claimed that “true” history revealed the lawful unfolding of a universal plan. Herbert Spencer in the last third of the 19th century and Arnold Toynbee and Oswald Spengler in the

early 20th century wrote universalist histories of humanity in this mode.

2. The other model was that of Leopold von Ranke, whose goal for historians was to “describe the way things actually happened.” Ranke challenged historians to give the most accurate and “objective” account of the past possible, employing “objective” in a new sense given to it in German scholarship.
- D. Interestingly, many American historians misunderstood Ranke, who emphasized the need to find the underlying causes of history. In contrast, at the turn of the 20th century, American historians saw themselves as engaged in a scientific enterprise, which therefore, from the perspective of the historian, had to be ruthlessly impersonal and factual.
1. Charles Beard and Carl Becker were prominent American historians who dismissed disinterested objectivity as a possible methodology for historians.
 2. All historical accounts inevitably reflected biases and value judgments, as Beard, in particular, showed in his 1913 book *The Economic History of the U.S. Constitution*, which argued that the Constitution was the product of economic rivalries among the Framers.
- E. World War I shattered the putative objectivity of even the most eminent historians.
1. A 1914 manifesto defending Germany’s goals and conduct of the war, entitled “To the Civilized World,” was signed by almost all leading German intellectuals (Einstein was conspicuous in his refusal to sign) in spite of being blatantly propagandistic and factually wrong.
 2. For their part, the overwhelming majority of British and French intellectuals supported their governments in the demonization of Germany and of Germans as an enemy and refused to allow German scholars to participate in conferences for years after the war.
 3. In the United States, the situation was much the same, particularly after entry into the war. Many historians (as most academics and intellectuals) supported that involvement. A National Board for Historical Service was formed in 1917 that produced written materials for the public and for schoolteachers to use to promote patriotism and U.S. involvement.
- F. What had become of objectivity? The hideous violence of World War I led many to dismiss as a myth the progress promised by a commitment to reason. In 1924, the historian James Harvey Robinson wrote, “I have come to think that no such thing as objective history is possible.”

- II.** Between 1930 and 1960, relativist historiography, that is, history writing that offered a particular interpretation of events, would be seriously challenged, even stigmatized, by world events.
- A.** With the Great Depression and the rise of totalitarian regimes in Russia, especially after Stalin achieved control in the late 1920s; in Germany with the election of Hitler in 1933; as well as in Italy with Mussolini (1922) and in Spain with Franco (1938), historians had to choose: Are these regimes to be described neutrally or valuationally?
 - B.** In the 1930s, relativism in history writing and more generally was stigmatized as destructive of social hope and solidarity, of a shared sense of right and wrong, and of belief in good and truth.
 - C.** With the outbreak of World War II, pro-war intellectuals attacked relativism as pathological, and Beard, who opposed Roosevelt's intervention and later revealed the means Roosevelt employed to win support for intervention, was a particular target. The historian community overwhelmingly committed itself to the discovery of universal values and objective history writing.
 - D.** After World War II, the German philosopher-historian Leo Strauss at the University of Chicago championed objective political analysis and history writing. In the 1980s, one of his followers, University of Chicago professor Alan Bloom, published *The Closing of the American Mind*, an argument against relativism and an appeal for a return to universal standards and objective value judgments.
 - E.** This intellectual climate of the late 1930s–1950s displaced the relativist position in historiography. Indeed, in the early 1960s, the *International Encyclopedia of the Social Sciences* depicted relativism as no longer viable intellectually.
- III.** But even as the obituary of relativism was being written, relativism was making a comeback, and with a vengeance.
- A.** From the 1960s–1980s, history was used as a means to debunk the idea of objective knowledge, including objective knowledge in the physical sciences. History undermined the modernist project, extending back to the 18th-century Enlightenment, that reason is the means by which progress is made.
 - B.** Remember that the 1960s were a flashpoint for anti-establishment protest, spawning movements to demand civil rights, oppose the Vietnam War, protect consumers and the environment, protest the influence of multinational corporations, and so on. These movements assailed science and technology as tools and accomplices of establishment power brokers.

- C. An intellectual consensus grew, outside the sciences, that this attack on the modernist program had merit. A crucial role in this critique was played, ironically, by historians of science and technology!
 - 1. Thomas Kuhn's 1962 *The Structure of Scientific Revolutions* precipitated a shift to externalist histories of science and technology that, over the next 20 years, made a compelling case for the influence of social and cultural forces and values on the conduct of science and technology.
 - 2. Before Kuhn's work, historians of science and technology practiced internalist history, tracing the technical development of theories or inventions with little reference to their social contexts. Now, the history of both science and technology began to explore the political, economic, and social factors underlying developments in these disciplines.
 - 3. In the 1970s–1980s, this shift marked the emergence of *post-modernism*: the critique of rationality as the self-evident means by which human beings come into contact with reality and make progress. In this view, reason is seen as an ideological device.
 - 4. Some externalist history of science had been written in the 1930s, primarily Marxist theories that had limited influence. In addition, in 1936, Robert Merton studied the influence on the Scientific Revolution of religious affiliations among the founding members of the Royal Society of London.
- D. History writing, then, became a powerful tool for attacking the status quo.
 - 1. The French intellectual historian-philosopher Michel Foucault focused attention on power relationships in shaping the ideologies called “knowledge.”
 - 2. The philosopher Jacques Derrida triggered a global craze for *deconstructionism*, a radically relativist assault on meaning and values that sparked the Science Wars of the 1980s–1990s.
- E. By the 1980s, however, a growing chorus of voices, including those of historians, was calling for a new, critically defensible concept of objectivity, pointing to the morally corrosive and socially destructive implications of post-modernism, deconstruction, and radical relativism.

Essential Reading:

Peter Novick, *That Noble Dream: The “Objectivity Question” and the American Historical Profession*.

Alain Renaut, *The Era of the Individual: A Contribution to a History of Subjectivity*.

Dorothy Ross, *The Origins of American Social Science*.

Questions to Consider:

1. If history writing is necessarily selective and interpretive, what value is it?
2. George Santayana is famous for saying, “Those who are ignorant of history are condemned to repeat it,” but could history ever repeat itself and how would we know it if it did?
3. How can historians reconcile relativism and objectivity?

Lecture Twenty-Nine

Culture—Linguistics

Scope: Linguistics is of special interest for several reasons. In the 20th century, linguistics shifted from a predominantly historical focus (the study of how languages have changed over time), to studying the nature of language as used: its form, function, and acquisition. A particularly influential early-20th-century theory of language was one that described language as a closed system of relationships, analogous to (but completely independent of) the relational interpretation of space, time, matter, and energy in the relativity and quantum theories. Cultural-behavioral and psychological-behavioral theories of language dominated the mid-century, to be supplanted by structural and cognitive theories in the late century.

Outline

- I. As we've discussed, one challenge confronting the social sciences as sciences is that they deal with subject matter that incorporates value judgments.
 - A. A second challenge is achieving methodological objectivity. In studying material that incorporates value judgments, is it possible to take a neutral methodological stance?
 - B. Anthropologists, political scientists, economists, historians, and sociologists all have these two challenges with which to contend. Archaeologists and linguists, however, would seem to be free of this problem; in this lecture, we turn to the field of linguistics.
- II. Modern linguistics began with the work of Ferdinand de Saussure in the first decade of the 20th century. De Saussure influenced many subsequent intellectuals and reoriented the study of language.
 - A. Eighteenth-century linguistics was interested in the origin of language; 19th-century linguistics was interested in the historical development of language. The 19th-century also saw the origin of a science devoted to collecting and studying languages.
 - B. Not surprisingly, in the second half of the 19th century, an evolutionary interpretation of the historical development of language became popular. Nineteenth-century linguistics also viewed languages as systems with coherent structures. Just as Georges Cuvier was able to reconstruct extinct creatures from a handful of fossil bones, one could do the same thing with languages.
 - C. Using this system orientation, de Saussure, as a young man, predicted the existence of a previously unknown vowel form in an extinct

language, and he was subsequently proven correct. In 1906, as a professor at the University of Geneva, de Saussure began teaching a course in general linguistics in which he presented his own, surprisingly radical, theory of language.

1. This theory was published in 1916 by former students from notes after de Saussure's untimely death in 1913. He had set aside *diachronics*, the study of how languages change over time, in favor of *synchronics*, how languages "work" at a given time as they are used. He was particularly interested in the origins of meaning.
2. De Saussure argued that all linguistic meanings and values derive from relationships among the sounds and signs of a language, with no necessary connection at all to what language refers to. For de Saussure, a language is a closed network of relationships.
3. This theory sounds similar to the claim in the general theory of relativity that the mass of an object is a function of the total masses of all the other objects in the universe. In the same way, the meanings and values of a language are a function of internal relationships.

D. For de Saussure, language was a social "fact." This idea echoes that of the French founder of modern sociology, Emile Durkheim, who asserted that social relationships exert forces on the members of society. In the same way, language causes us to behave the way we do linguistically.

1. Therefore, the focus of linguistics was on *semantics*, the meanings of words, as opposed to *syntax*, grammatical rules.
2. These ideas are also similar to those of David Hilbert, with his formalist interpretation of mathematics as a closed system of logical relationships.

III. Contemporaneously with de Saussure, Franz Boas became very influential in linguistics in the United States, because of his relativist culture perspective.

- A.** Boas pioneered the study of native languages, native North American languages in his case, as opposed to the previous almost exclusive focus on the ancestry and "heirs" of the classical languages, Greek and Latin, primarily. Boas's relativism generated a school of linguistics that studied languages in their particular cultural contexts.
- B.** Two of Boas's followers, Benjamin Whorf and Edward Sapir, formulated the hypothesis that each language represents a certain way of experiencing the world.

- C. Leonard Bloomfield began with Boas but initiated an empirical-behavioral school of linguistics that linked language to behavioral psychology and its methodologies.
 - D. *Descriptivism*, theory-neutral descriptions of languages and their rule systems, emerged in the 1940s and 1950s as a further development of Bloomfield's empiricist-behavioral approach.
 - E. Descriptivism, in turn, gave rise to structuralism, that is, the attempt to discover the rules underlying the use of a language, the structural rules that are exemplified in the syntax of a language, rules of which speakers are unconscious even as they "obey" them.
 - F. From 1925—1950, the Prague school of functional linguistics focused on identifying the network of relationships among the functional elements of a language.
 - G. Zelig Harris, at the University of Pennsylvania, was a particularly successful and influential proponent of descriptive-structural linguistics into the 1950s. Harris's most enduring impact on linguistics, however, may be his influence on Noam Chomsky, who as a graduate student at Harvard, was also influenced by Roman Jakobson, the most prominent member of the Prague school.
- IV. Chomsky synthesized the work of Jakobson and American descriptive-structuralist linguistics.
- A. In 1957, Chomsky published *Syntactic Structures*, a small book that transformed the field of linguistics even more quickly and more deeply than de Saussure's book had.
 - B. Chomsky set aside questions of semantics and de Saussure's "social fact" and focused on syntax as the key to linguistic behavior.
 - C. His commitment was almost violently anti-behavioral. For Chomsky, language competence cannot be acquired behaviorally, because very young children quickly display an ability to generate an unlimited number of sentences that they have never heard.
 - D. Chomsky was also anti-Boasian in his insistence that linguistic competence is a universal neurological capability. At a deep level, all languages are, in principle, inter-translatable.
 - E. Chomsky's search for an absolute linguistic structure gave rise to an extraordinarily prolific and fertile research program that dominated linguistics in the 1960s–1980s.
- V. Late-20th-century linguistics has qualified its enthusiasm for Chomsky's approach, and other approaches to understanding language have emerged.
- A. Not surprisingly, one of these schools has focused on semantics.

1. De Saussure made a distinction between *parole*, the sounds made by speakers of a language, and *langue*, the underlying, abstract structure of a language.
 2. Chomsky made a distinction between *competence*, the neurological capability of speaking, and *performance*, again, the sounds speakers make.
 3. A more moderate position emerged in the late 20th century calling for linguistics to focus on how people communicate.
- B.** George Lakoff and collaborators have developed further the Boas-Sapir-Whorf claim that each language encapsulates a distinctive way of experiencing the world. They explore language's metaphorical character as revealing universal structures of unconscious bodily awareness. This school brings biology, cognitive psychology, and genetics into linguistics.
- C.** Finally, some linguists have argued for a more comprehensive relational grammar than Chomsky's, in which form, substance, content, and expression are equally weighted parameters of language.

Essential Reading:

Ferdinand de Saussure, *Course in General Linguistics*.

Roy Harris, *Language, Saussure and Wittgenstein: How to Play Games with Words*.

Geoffrey Sampson, *Schools of Linguistics*.

Questions to Consider:

1. If a language is a closed system of relationships, how can it refer to anything outside language?
2. If language as a social fact exerts forces on its speakers, how do speakers cause linguistic change (for example, via slang, metaphors, and so on)?
3. Is translation from one language to another possible for a Boasian? For a Chomskyan?

Lecture Thirty

Society—Sociology

Scope: Sociology is, conceptually at least, subsumed under anthropology and subsumes political science. What is a society? What distinguishes it, what keeps it together over time, what are the laws of its functionality? In the mid-19th century, Auguste Comte invented the term *sociology* as the name of a new science of society, conceived along Baconian-Newtonian lines. Comte, with Marx, John Stuart Mill, Herbert Spencer, and Emile Durkheim, created the core legacy of social and political science that the 20th century inherited, including a deep ambivalence between description and prescription. Twentieth-century sociology moved from grand theories of society to the detailed study of social processes and institutions.

Outline

- I. In the course of the 20th century, sociology evolved from a science of grand theories of “society” to a science of social relationships and processes.
 - A. The 19th-century legacy of social theory was formidable, including Auguste Comte, Karl Marx and Friedrich Engels, John Stuart Mill, Herbert Spencer, and Emile Durkheim.
 1. Comte invented the term *sociology* and, beginning in the 1820s, formulated a truly grand theory of humanity’s cognitive evolution within which his theory of society found its basis.
 2. Comte focused on how the human mind had evolved from its earliest animist beginnings through polytheism, monotheism, and a metaphysical state of mind in the post-medieval world, to the scientific, or *positivist*, state of mind.
 3. Comte’s goal was a reason-driven society that balanced order and progress, social statics and dynamics, the former to be anchored in conservative universal religious rituals, the latter to be managed by a council of industrialists and scientists.
 - B. Marx and Engels were deeply committed to a materialistic and deterministic theory of society, in which social evolution is driven by unstable forces (greed, private property, and pursuit of self-interest) until society reaches an equilibrium state, called *communism*. After 1859, Marx was strongly influenced by Darwin, to whom he wanted to dedicate *Kapital*, such that society moved by directed evolution to a classless, equilibrium condition.
 - C. John Stuart Mill’s social theory, consistent with his induction-based philosophy, proposed an empirical search for principles underlying social relationships that exist in society.

- D. Herbert Spencer defended a radically materialistic, deterministic theory of cosmic evolution that incorporated the emergence of man, values, and society.
 - E. In retrospect, Emile Durkheim stands out as the first “modern” sociologist.
 - 1. For Durkheim, *society* was a name for the network of relationships that caused the members of that society to behave in specific ways. Further, a primary objective of every society was to communicate to its members a sense of solidarity.
 - 2. The 19th century saw society itself as having an abstract existence independent of its concrete manifestation. Durkheim redefined the concept of *society* as a much more concrete entity.
 - 3. Durkheim’s network of relationships can exercise forces on people in subtle ways; notice that this idea is similar to what de Saussure said about language.
- II. Twentieth-century sociology extends the Durkheimian approach to sociology without adopting his particular theory.
- A. The first great 20th-century sociologist was the Italian Vilfredo Pareto.
 - 1. For Pareto, who also wrote extensively on topics in economics and political science, “society” was a name for an aggregate of correlated individuals, each of whom is driven by non-logical, psychological/emotional motives.
 - 2. Pareto developed a true systems approach to society and the economy (in its modern sense), an approach that was naturalistic and employed a “logico-empirical,” that is, inductive, methodology but was not rational in the traditional sense of that term.
 - 3. Nevertheless, in a manner similar to the kinetic theory of gases, radioactive decay, R. S. Fisher’s population genetics, and late-1920s quantum mechanics, Pareto argued that the behavior of a society as a whole can be lawful even if the behavior of each of the individuals making up that whole is not.
 - B. Max Weber is perhaps best known for his study of the relationship between Protestantism and the rise of capitalism.
 - 1. Weber promoted a humanistic, as opposed to a naturalistic, sociology, one in which only individuals act; only individuals, as nodes or atoms of the networked social reality, are “carriers” of value and meaning.
 - 2. For Weber, all action by individuals is driven either by tradition or by affect, which as for Pareto, is not irrational but is not rational in the philosophical-scientific sense.
 - 3. Capitalism, for Weber, is a mode of social organization in which the values of efficiency and rationality play a dominant role. Note the highlighting by Weber of efficiency and the characterization of

rationality as a value: modern society places a value on rationality; rationality is not intrinsically valuable.

- C. Typically, American social science, which became increasingly influential in the 20th century, was less theory-centered than European social science and more fieldwork-centered.
 - 1. American pragmatism, developed by John Dewey and others, asserted that human behavior is instrumental; that is, it matches means to ends. Members of society look for effective behaviors in constantly changing environments.
 - 2. Pragmatism incorporated chance, contingency, novelty, possibility, progress, and freedom into an activist, optimistic philosophy.
 - 3. Pragmatism offers a process-centered interpretation of experience and, therefore, rejects dichotomous thinking.

III. Although the mid-century saw important European intellectual contributions, American empirical and functional sociology stands out.

- A. Just before World War II, the Frankfurt school of social philosophers, transplanted to the United States on the eve of the war, exerted influence on social theory, as did the foundation of sociology of knowledge. Karl Mannheim was a leading figure in applying sociology to knowledge, extending the concept of *ideology* to all forms of knowledge except science and mathematics. As we know, in the 1960s, scientific knowledge would also be identified as ideological.
- B. Meanwhile, American academic institutions became deeply committed to a social reform agenda while performing social science research.
 - 1. The Chicago School of Urban Studies, for example, produced a series of research monographs on poverty, the black ghetto, suicide, immigrant communities, and so on.
 - 2. Concurrently, the *Yankee City* series edited by W. Lloyd Warner documented social life in a number of northern cities.
 - 3. Most famously, perhaps, the Lynds produced *Middletown*, a loosely disguised, closely detailed longitudinal social study of a single American industrial town (Muncie, IN) from 1924–1937.
- C. Post-World War II sociology continued to move away from grand theories to social process studies.
 - 1. The first dominant postwar figure in American sociology was Talcott Parsons, who had developed a functionalist approach to sociology: identifying functional elements in a society and the relationships among those elements. This model transformed into a structuralist view in the 1960s–1970s.
 - 2. In the 1970s–1980s, sociologists and political scientists, perhaps more than any other group of scientists, embraced post-modernism and the associated critique of reason, rationality, and progress. Science and technology were included as part of Mannheim's

sociology of knowledge; they, too, were seen as ideologies, not purely neutral descriptions of reality or neutral inventions.

3. At the end of the 20th century, sociology experienced a methodological fragmentation, analogous to that seen in anthropology, and seemed to be searching for a new disciplinary direction at the turn of the 21st century.

Essential Reading:

Randall Collins, *Four Sociological Traditions: Selected Readings*.

Dorothy Ross, *The Origins of American Social Science*.

Rob Stones, *Key Sociological Thinkers*.

Questions to Consider:

1. In what sense are societies more than the sum of the individuals who comprise them?
2. Do people deliberately choose the ways in which they associate with one another?
3. Is the goal of sociology describing how people, in fact, live together or identifying how they might or ought to live together?

Lecture Thirty-One

Society—Political Science

Scope: Within the broad framework of social theory, political science is concerned with the relationships of power and authority that provide an infrastructure for the functional unity of “a people.” Classically focused on “the State” as the source of this unity, in the early 1900s, political scientists began to substitute the government for the state. Especially in America and England, the viability of a pluralistic society under a democracy and/or with a “liberal” government became the dominant political scientific issue from the teens through the 1920s and up to World War II. In the 1950s, pluralist theory gave way to a behavioral conception of political science, but in the late 1960s and early 1970s, behaviorism was overthrown in the rush to affirm a post-modern interpretation of political phenomena. Political science fractured into many at least seemingly different self-conceptions, based on, among other things, game theory, rational choice theory, and voting model analysis.

Outline

- I. What is the source of the unity in a society that anchors relationships of power and authority?
 - A. In the early 20th century, the dominant concern of political science in Europe was with “the State.”
 1. Americans have difficulty fully understanding the term as it was used and thought of by Europeans.
 2. The State embodied the *organic unity* of a people; the ruler was the embodiment of the State and, therefore, the source of all meaning and value, all power and authority.
 3. Even today, after many countries on the Continent have become democratized, their governments remain far more centralized than that of the United States.
 4. Classically, the State is more than just power and authority; it also embodies the ideals and purposes of a society.
 5. America and Great Britain, at the beginning of the 20th century, represent a revolutionary transformation of thinking, with the substitution of elected government for the State.
 6. The government, in American terms, is a negotiated, pragmatic unification of a fragmented population’s changing, competing interests. It is not invested with the same authority and meaning as the State.
 - B. The European and the American approaches had profoundly different consequences for political theory and institutions.

1. America, and to some extent Great Britain, has a radically, aggressively pluralistic society, in which formation and pursuit of special interests is legitimated.
 2. Despite the competition of these special interests, the commonality of the United States has somehow survived, even under such stresses as the Great Depression, World War II, the Vietnam War, and so on.
 3. How a collection of competing special interests can achieve enough unity to function effectively became the central issue for political science in the first half of the 20th century.
- C. Toward the end of the second decade of the 20th century, Harold Laski, a progressive political scientist at Harvard University, became a mouthpiece for the positive value of political pluralism: for party politics, the free formation of special interest groups, and for competition among these groups as defining a public interest that is constantly subject to change.
1. Laski lost his position at Harvard after defending the right of the Boston police to strike in 1919 and moved to Yale, returning to England in 1920, to the London School of Economics*.
 2. Nevertheless, in the 1920s and 1930s, Laski's theory of democratic government based on contending individual wills became a strong influence on such powerful U.S. jurists and legal theorists as Roscoe Pound, Oliver Wendell Holmes, Jr., and Felix Frankfurter, among many others. Holmes, in particular, argued that law is not based on principle; it is based on a negotiated, pragmatic compromise between social circumstances and legal principles.
- D. Concurrently, a core of intellectual elitists rejected the efficacy of pluralistic democracy and advocated the control of public opinion through "white propaganda."
- E. Further, the modern industrial corporation emerged in the 1880s in the United States and, by World War I, dominated the marketplace as a powerful political institution.
1. Anti-trust legislation was implemented from the 1890s to protect the public unity, but of course, corporations sought ways to circumvent such regulation.
 2. This development led political science to question whether corporate capitalism is compatible with a pluralistic democracy.
 3. C. Wright Mills's *The Power Elites* was a classic 1950s challenge to the robustness of democracy to protect the pursuit of individual self-interests from the pursuit of corporate interests.
- F. In the 1950s and 1960s, political science underwent a behavioral "revolution," shifting its focus to describing how political institutions and political processes actually worked in the "real world." Of particular interest was the question of why American and British

political institutions and processes continued to function in the 1930s, under extreme pressure, when almost all the post-World War I liberal governments put in place in Europe had fallen into the hands of ultra-conservative or totalitarian parties.

- II. Behaviorism in political science had run its course by the 1970s, as it had in psychology and the social sciences, and political science took yet another turn.
 - A. Between 1900 and 2000, political science moved from a focus on individual institutions to a focus on the network of political institutions and their functional interrelationships.
 - 1. Institutions now appear as systemic ordering mechanisms, not “atomic” responses to particular problems. Political science adopted a holistic, system-level view of society.
 - 2. This echoed the rise of functionalism in sociology and, again, resulted in a move toward structuralism in the 1980s.
 - B. The 1990s saw a turn by political scientists to neo-institutionalism, an attempt to apply “harder” techniques borrowed from economics, such as game theory or rational choice theory, to the study of institutions.
 - 1. Neo-institutionalism reflects prevailing ideas that political structures in society never achieve equilibrium. Instead, the goal for the political process is to achieve equilibrium *plateaus* that will always be upset by changes in the environment.
 - 2. This view of the American system as an open-ended, dynamic process echoes Harold Laski’s ideas in 1910–1920.
 - C. At the end of the 20th century, however, as at the beginning, there remained a decisive split between Europe, indeed effectively all of the world, and the United States, where the function of institutions is to impose commonality on individual social atoms with no intrinsic connections to one another.

Essential Reading:

John Dryzek, et al., *Political Science in History: Research Programs and Political Traditions*.

Mark Mazower, *Dark Continent: Europe’s Twentieth Century*.

C. Wright Mills, *The Power Elite*.

Questions to Consider:

- 1. How can a pluralistic democracy survive competition among contending special interests, each pursuing their own good?
- 2. Is there such a thing as “the public interest” in a pluralistic democracy and how is it defined?

3. What do we gain, practically speaking, from understanding how our political processes and institutions function?

* *Clarification:* Harold Laski spent a year at Yale after leaving Harvard in 1919 and, on returning to England, joined the faculty of the London School of Economics. Laski's university training was at New College, Oxford University.

Lecture Thirty-Two

Society—Economics

Scope: The formulation of general theories of economic behavior that were capable of generating new economic policies was a late-19th/early-20th-century development. The pioneering efforts involved mathematical models of equilibrium in supply-demand relationships, assuming “rational” choices on the parts of suppliers and consumers. In the second half of the century, major developments included the adoption of game theory mathematics, the growth of econometric models enabled by computers, the integration of economics and law, and attacks on the notion of rationality employed in classical economic theory, for example, Herbert Simon’s notions of *satisficing* and *bounded rationality*, and Daniel Kahneman’s research into the “irrationality” of real behavior, both of these efforts receiving Nobel Award recognition.

Outline

- I. Perhaps the greatest accomplishment of economists in the course of the 20th century was to create a new reality; “the economy” has become similar to “the State” in 19th-century Europe that we discussed in the last lecture.
 - A. Historically, the term *economy* was used to refer to a well-ordered whole; it did not have specifically commercial connotations.
 - B. In the 20th century, *economics* became a name for the attempt to understand how the commercial relationships in a society can be a well-ordered whole.
- II. Like sociology, 20th-century economics is deeply indebted to developments in 19th-century economics.
 - A. A “marginalist revolution” was precipitated in 1871 by W. Stanley* Jevons in England, Carl Menger in Austria, and Leon Walras in Switzerland, who independently (re)discovered the principle of diminishing marginal utility.
 - B. These three thinkers were not the inventors of economic theory. Adam Smith, David Ricardo, and John Stuart Mill were probably the leading economic thinkers in the late 18th and early 19th centuries.
 - 1. They conceptualized the notion of economics as a science, with the goal of discovering the conditions of equilibrium in the commercial structure of a society. *Equilibrium* was the “balanced circulation” of goods and income.
 - 2. These three men shared the idea that economic values were objective and keyed to real costs, that is, the costs of production.

- C. The marginalist revolution was a conceptual one, asserting that economic decisions had a subjective character; in making an economic decision, a prospective purchaser or seller takes into account the principle of diminishing marginal utility.
 - 1. Further, marginalists argued that the actual costs of any economic decision are opportunity costs.
 - 2. These subjective factors complicated the attempt to find an equilibrium condition, prompting the marginalists to use more elaborate mathematical models to discover the condition in which supply and demand are balanced, given the principle of diminishing utility.
 - 3. Jevons made significant contributions to symbolic logic and to probability theory, especially the notion that probabilities were measures of rational expectation.
 - 4. Walras's goal was discovering stable equilibrium solutions for algebraic supply-and-demand equations, assuming "pure" exchanges (in which supply and demand both derive from utility maximization), in a competitive market.
 - D. Early-20th-century economics was marked by a dispute between the marginalists and Alfred Marshall, but important ideas were being developed by others that would bear fruit later in the century.
 - 1. Marshall disapproved of the deductive reasoning employed by the marginalists, favored "real" costs and objective values, and sought to explain how utility-based demand and real cost-based supply interacted in actual markets. This concrete approach dominated British thinking until the 1930s.
 - 2. Meanwhile, Austrian economic theorist Joseph Schumpeter, a student of the Menger School*, in 1911 identified entrepreneurship and technological innovation as the engines of economic growth, but attracted little attention at the time.
 - 3. Walras' student and successor Vilfredo Pareto added social optimization to Walras's algebraic equations. According to Pareto, to achieve economic equilibrium, social utility, as well as individual utility, must be part of the equation.
 - 4. In America, Thorstein Veblen and colleagues sought to understand how social, historical, and institutional factors affected economic change. *Institutionalist economics* was highly influential in the United States for the first decades of the century but virtually disappeared in the 1920s.
- III. The dominant figure of mid-20th-century economics was John Maynard Keynes.
- A. Keynes was a well-connected Cambridge academic who made economic theory a tool of government policy, in the process inventing macroeconomics.

1. Keynes was a member of the British Versailles delegation and resigned because of his disapproval of its terms. In the early 1920s, he was vocal on a number of public issues in England. In the 1930s, he published a theory of monetary policy that was savaged by his lifelong rival Friedrich Hayek; Keynes responded by forming a research team at Cambridge.
 2. In 1936, synthesizing the results of this team's work and his own ideas, Keynes published his epochal *General Theory of Employment, Interest, and Money*, which became, and remained, a blueprint for government management of the economy.
 3. Keynes argued that economic stability was a government responsibility, promoting deficit spending to create employment through public works, dismissing fears of budget deficits. His theory explained aggregate economic output and employment as a function of aggregate demand and showed that this would, ideally, lead to a demand-derived equilibrium without unemployment.
- B.** Keynes's ideas were adopted by governments before and after the war.
1. In 1940, Keynes published an essay, "How to Pay for the War," whose recommendations, compulsory saving and rationing, became Britain's anti-inflation policy, and extended his general theory, which dealt with recession.
 2. Though ill, he led the British delegation to Bretton Woods and was instrumental in creating the International Monetary Fund and the World Bank.
- C.** The London School of Economics and Political Science (LSE) was created in 1895 as a research-plus-teaching institution and, in the 1930s, blossomed as a center of economic theory.
1. Lionel Robbins, who came to LSE as chair of economics in 1932, rejected Marshallian ideas and ushered marginalist economics, through Pareto, into British economic thought. Robbins also brought a number of brilliant, young economists to LSE, who substantially developed Pareto's ideas.
 2. Recall that Pareto's thought was keyed to including social optimization, along with individual optimization, in economic decision making. Could economics as a science identify social optimization, when doing so implies a value judgment?
 3. One of the most seminal thinkers at LSE and, later, Harvard was Paul Samuelson, who was responsible for bringing extremely sophisticated mathematical techniques into economics in the post-World War II era.
- D.** At the University of Chicago, Milton Friedman was a lifelong opponent of Keynes, in that he believed economic output is determined by monetary policies, not income-expenditure models.

- IV. Behind the grand economic equilibrium-seeking theories of the first half of the century, mathematical tools took center stage in the second half of the century and led to a reconsideration of rationality.
- A. In 1943, John von Neumann and Oscar Morgenstern published their *Theory of Games and Economic Behavior*, which formalized choice under risk and uncertainty by providing rules for calculating expected utility.
 - B. Ironically, in the mid-1950s, Leonard Savage derived the same expected-utility measures using subjective, rather than objective, probabilities, and Kenneth Arrow and Gerard Debreu arrived at the same results without using probabilities at all.
 - C. The most dramatic conceptual turnabout in economics has been in the last 10 years, with the impact of work begun in the 1970s by Daniel Kahneman and Amos Tversky. They argued on empirical grounds that people are not efficient, “rational” decision makers who are focused on maximizing their utility.
 - 1. Kahneman and Tversky in effect extended Herbert Simon’s argument in the 1960s that institutional decision makers displayed *satisficing*, not maximization, under conditions of *bounded rationality*.
 - 2. These theories were supported by studies in the 1990s at three universities using real-time PET brain scans and game-playing to reinforce the view that decision-making is emotional and that people do not know what their best interests are so they cannot be utility maximizers!
 - D. At the beginning of the 21st century, then, economic theory must adapt itself to the non-rationality of human decision-making.

Essential Reading:

By far the best reference source for the history of economics is the web site *History of Economic Thought* maintained by the New School for Social Research in New York City: www.cepa.newschool.edu/het/

Supplementary Reading:

Robert Skidelsky, *John Maynard Keynes: Fighting for Freedom, 1937–1946*.

Questions to Consider:

- 1. How can there be a science of economics if decision making is not a rational process?
- 2. How can economists, as social scientists, identify the values that ought to underlie societal economic policies?
- 3. In what sense is “the economy” a reality?

* *Clarification:* Joseph Schumpeter was a student of the Menger School and was a middle-aged man when he came to Harvard.

Lecture Thirty-Three

Mind—Classical and Behavioral Psychology

Scope: By the late 19th century, mind was the last bastion of human privilege, the only natural phenomenon not (yet) reduced to deterministic, materialistic processes, but it was under attack. But mid-19th-century neurophysiology laid the foundation for a materialist theory of brain activity and of consciousness itself. At the turn of the 20th century, mind became problematic. On the one hand, the new discipline of experimental psychology was challenging the claim that we knew our minds and clinical psychology was accumulating case studies that reinforced this conclusion. Freudian psychology was built on the claim that most mental processes, and all of our desire-driven actions, were unconscious in origin, and Jung extended the unconscious into history through his concept of the collective unconscious. Concurrently, behaviorism, which dominated the scene from the 1930s to the 1970s, dismissed consciousness as a causally significant factor for explaining human behavior, while Gestalt psychology dismissed behaviorism. After the 1970s, both were supplanted by cognitive psychology.

Outline

- I. Philosophers have tried to understand the mind at least since the time of Aristotle, but scientific psychology is a product of the last quarter of the 19th century.
 - A. Wilhelm Wundt created the first experimental psychology laboratory in 1875 and, in 1895, the first research institute for experimental psychology. As we will see, the evolution of psychology, from the early-20th-century introspective psychology of Freud to the cognitive neuroscience of the 1990s, is a resumption of the experimental agenda that Wundt mapped out.
 1. Consciousness, for Wundt, is the reality that is the subject of psychology; his research interests included perception, memory, learning, and reasoning.
 2. Wundt's conception of humans was that they are willful and emotional beings, not primarily rational. Reasoning is not the essential characteristic of our nature.
 - B. Wundt had a considerable influence on the first American to teach experimental psychology, William James, a member of the intellectual circle that created pragmatism. James was also a member of the philosophy faculty at Harvard, but in the late 1880s, changed his faculty identification to psychology.

1. James taught Wundt's ideas in the classroom and hired a student of Wundt's, Hugo Munsterberg, who directed and expanded James's experimental psychology lab at Harvard.
 2. In 1890, James's *Principles of Psychology* appeared, introducing the term *stream of consciousness* and adding to Wundt's agenda the phenomenon called *selective attention*. James took the position that consciousness had a systemic or holistic character, reflecting internal organizational principles; it is not just a random collection of inputs from the senses.
 3. The research agenda that James mapped out would manifest itself 30 years later as Gestalt psychology.
- C. Wundt and James developed one type of introspective psychology that was concerned with how the mind organizes sensory perception so that we experience the world in an organized fashion. Another type of introspective psychology was that of Freud.
1. Freud and his mentor, Josef Breuer, published *Studies in Hysteria* jointly in 1895, but Freud stepped out on his own in 1900 with *The Interpretation of Dreams*. Freud's famous theory of repression emerged from his study of "hysterical" patients. He developed psychoanalysis as a technique for helping patients release repressed material, which according to Freud, is the source of all neurotic and psychotic symptoms.
 2. The most important aspect of Freud's thought is his insistence that human behavior is driven by unconscious motives. Thus, the unconscious became the subject of psychology.
 3. Freud's "map" of the mind involved the unconscious *id*, seat of the pleasure principle; the conscious (and preconscious) *ego*, seat of the reality principle; and the *superego*, which manifests itself as the conscience and as the ego ideal. Repression and conflict were fundamental features of this internal landscape and, for Freud, the physical manifestations of repression and conflict could always be traced to childhood sexual trauma.
- D. Jung was, initially, an enthusiastic Freudian but broke with Freud in 1911, when he began to suspect that he was being groomed as Freud's Christian "mouthpiece."
1. From 1914 to 1927, Jung went through a self-described "dark" period in which he explored his fears, anxieties, fantasies, and dreams.
 2. He emerged as an "explorer" of the unconscious, specifically, the *collective unconscious*. This term can be defined as universal patterns for organizing experience that manifest themselves in dreams, visions, mythology, religion (especially mysticism), alchemy, art, and literature.
 3. By studying these manifestations of the collective unconscious, we can discover the *archetypes* that all human beings share because of

our common biological history. One of these archetypal patterns is called the *self*.

- II. Freud and Jung's focus on the unconscious mind stands in contrast to the emphasis of behaviorism.
 - A. John Watson in 1913 announced his decisive break with all forms of introspection-based psychology, proclaiming that the subject of psychology was not mind or consciousness, but the prediction and control of behavior.
 - 1. Watson was influenced in this by Pavlov's work on conditioned reflexes and Edward Thorndike's 1911 text, *Animal Intelligence*.
 - 2. Thorndike proposed two laws of animal intelligence: Behavior is determined by its consequences, and behavior is reinforced by repetition.
 - 3. Watson was forced to resign from Johns Hopkins in 1921 and joined the J. Walter Thompson advertising agency, successfully applying his academic research.
 - B. Beginning in the mid-1930s, behaviorism was increasingly identified with the work of B. F. Skinner.
 - 1. Skinner's 1938 *The Behavior of Organisms* revived Watsonian stimulus-response behaviorism on more sophisticated grounds. Skinner emphasized *operant*, or adaptive, conditioning and the importance of schedules of reinforcement.
 - 2. For Skinner, people do not act; they react to the environments in which they find themselves. Mind, body, and personality are of no relevance to psychology, only patterns of reaction to environments, which can be designed to elicit any reaction desired.
 - 3. His controversial 1971 book, *Beyond Freedom and Dignity*, argued that a person's behavior could be adjusted in the same way that NASA adjusts one of its spaceships.
- III. Gestalt psychology emerged at the same time as behaviorism and in opposition to it.
 - A. Gestalt ("form" in German) psychology extended James's notion of how the mind organizes experience. For Gestalt psychologists, conscious experience has a holistic character that reflects innate structuring by the mind: The mind is not a passive receiver of external stimuli but actively organizes and interprets them.
 - B. Gestalt psychology was founded by Max Wertheimer, Kurt Koffka, and Wolfgang Kohler at Frankfurt in 1910–1914. All three fled the Nazis to the United States and settled at various universities.
 - C. In the period 1920–1930, the three published seminal works on such subjects as the figure-ground distinction, perception, and recognition of movement.

- D. The Gestalt psychologists were interested in selective attention and the fact that selectivity comes from inside the observer. From this point of view, Gestalt psychology was in sharp tension with behaviorism, which asserted that the mind was irrelevant.
 - E. In the 1930s, Kurt Lewin began his influential Gestalt-based research on group dynamics, conflict, and the “life space” of the self, and Gordon Allport published his Gestalt theory of personality, but behaviorism remained the dominant theory in psychology until the 1960s.
- IV. In the 1970s, behavioral psychology was displaced by cognitive psychology, in which mind matters once again!
- A. Ulric Neisser’s 1967 text, *Cognitive Psychology*, and the founding in 1970 of the *Journal of Cognitive Psychology* heralded a challenge to behaviorism and spawned a new scientific discipline.
 - B. Cognitive psychology resumes the central role for mind that it had had from Wundt through the Gestalt theorists. Its major themes include memory, learning, and reasoning—all central to Wundt’s research program.
 - C. In the last 25 years of the 20th century, we see a shift toward the scientific study of mind and mental processes, and we now have much more powerful tools with which to study these processes.
 - 1. Functional MRI devices and PET scanners, for example, allow us to observe mental processes in real time.
 - 2. This technology has enabled imaging of the brain as subjects engage in learning, speaking, reasoning, and so on.
 - D. Some of the discoveries being made in the correlation of brain and mind are disconcerting. For example, research supports the idea that conscious will is an illusion.
 - E. In our next lecture, we turn to artificial intelligence research and its connections to cognitive psychology.

Essential Reading:

Sigmund Freud, *The Ego and the Id*.

Carl G. Jung, *Archetypes and the Collective Unconscious*.

B. F. Skinner, *Beyond Freedom and Dignity*.

Daniel N. Robinson, *An Intellectual History of Psychology*.

Questions to Consider:

1. What was the appeal of behaviorism that it rose to dominance and remained dominant for decades in spite of denying that mind mattered?

2. If consciousness turns out to be a merely superficial phenomenon, in what sense is cognitive science an advance over Freud and Jung?
3. How did Freudianism, in which our actions are driven by unconscious, barely controllable drives, prove so powerful a cultural influence for the first two-thirds of the 20th century?

Lecture Thirty-Four

Mind—Cybernetics, AI, Connectionism

Scope: The idea that thinking is a deterministic physical process is an old one, already present in the 17th century. But in the 1940s, with the convergence of the new science Norbert Wiener called *cybernetics*, the realization of Alan Turing's conceptual computer, and the McCulloch-Pitts model of the neuron, this idea became a *scientific* idea. Inevitably, the mind was modeled as a computing machine and, thus, as an information-processing "device." Early work by Simon and Newell and by Minsky and Papert suggested that a thinking machine could be built based on a Turing computer, dismissing an alternative approach named *neural nets*. These two approaches reflect profoundly different conceptions of thinking and of rationality. Meanwhile, ever-more powerful experimental equipment allowed identifying increasingly specific correlations between mind and brain. By the end of the century, ironically perhaps, evidence was mounting that the initiation of action preceded conscious willing, which, if validated, would make consciousness at best only indirectly relevant to a causal theory of behavior and, perhaps, irrelevant after all!

Outline

- I. In the last lecture, we discussed the strands out of which cognitive psychology was woven, including the work of Wundt and James and the Gestalt psychologists. Another major influence that led to cognitive psychology and its expansion into the broader field of cognitive science is the field of artificial intelligence (AI), which is itself closely tied to *cybernetics* (machine control theory).
 - A. Between 1942 and 1952, the Josiah Macy Foundation sponsored a series of conferences that, inadvertently, brought AI into being.
 1. The foundation's goals were to identify the behavioral changes that would prevent future wars, and to that end, a broad spectrum of thinkers was brought together to "brainstorm" for a few days.
 2. The foundation's agenda was co-opted by scientists with innovative ideas for how the mind works, how the brain can be modeled, and how human-like behavior can be demonstrated in machines.
 - B. From the start, the conference series was astonishingly rich in innovative theories.
 1. Warren McCulloch, a biologist who chaired all 10 meetings, and his collaborator Walter Pitts, an electrical engineer, presented a binary electrical model of the neuron and of neuronal networks that could mimic the way in which the nervous system seemed to

- function. A mathematician conference participant, Lorente de No, commented that the human nervous system might be interpreted as a kind of computing machine.
2. At the same meeting, John von Neumann gave a presentation on the electronic digital computer, having accidentally learned of the ENIAC project at the University of Pennsylvania. He also described Alan Turing's work and predicted that a computer could be built to solve any mathematical problem for which it was given an algorithm.
 3. Norbert Wiener described how machines with feedback circuits and homeostasis, discussed at the conference by Arturo Rosenblueth, displayed adaptivity and apparently purposive behavior, implying that human purposive behavior was just an example of feedback processes in a more complex system.
 4. In 1943, Alan Turing published *Machine Intelligence*, which further advanced the idea that human reasoning is a form of computing and, therefore, a computer could be said to reason.
- C. Especially in the period 1946–1948, these conferences served to promote mutually reinforcing and productive interactions among the participants.
1. Between 1946 and 1948, Wiener developed his cybernetic theory of how feedback loops could be used to adjust the behavior of machines.
 2. Wiener linked cybernetics to the emerging theory of information that Claude Shannon and Warren Weaver were developing in the mid-1940s.
 3. In 1948, Shannon and Weaver showed that electrical circuits could implement the rules of propositional logic, creating the central design tool for electronic computers that is still used today. At the same time, McCulloch showed that his neural network models could perform these operations as well and, by incorporating feedback, could display memory (and later, learning).
 4. In 1948, von Neumann oversaw construction at Princeton of EDVAC, the first stored-program computer. EDVAC's serial algorithmic software architecture became the de facto standard for virtually all digital electronic computers into the 21st century.
 5. The alternative to the von Neumann architecture was the McCulloch-Pitts neural net architecture, to which we will return.
- II. In 1956, the pioneer computer scientist John McCarthy convened a conference at Dartmouth University and coined the term *artificial intelligence* as its theme.
- A. The implementation of computer programs that could “reason” was already underway by 1956.

1. In 1952, Arthur Samuel at IBM began a 10-year-long development of computer programs that could play checkers, eventually at world-championship levels.
 2. In 1955, Herbert Simon and Alan Newell published a program called “Logic Theorist”; they followed this up in 1957 with “General Problem Solver”, which could solve a wider range of problems.
- B.** In 1963, the Defense Advanced Research Projects Agency (DARPA) gave MIT a grant to pursue machine-aided cognition research, and the rate of development accelerated.
1. The MIT AI Lab was created, and Marvin Minsky emerged as a leader of the *top-down approach* to AI, in which mind is interpreted as computing with symbolic representations.
 2. In short order, “smart” software appeared, based first on the “microworld” concept and, from 1975, on what Minsky called *frames* (knowledge representation schemes). One example of these software programs was “SHRDLU”, which enabled a computer to manipulate blocks according to instructions.
 3. In 1975, “meta-DENDRAL” was the first program to make a scientific discovery. In 1974, “MYCIN”, the first expert system program, was demonstrated and, in 1979, extended to a commercial product, the same year that “INTERNIST”, the first medical diagnostic program, was published.
- C.** Between 1970 and the early 1980s, the accomplishments of the MIT AI Lab reinforced the validity of Minsky’s top-down approach.
1. To forestall the potential of infighting about this approach, Minsky and a colleague, Seymour Papert, published a devastating critique of the McCulloch-Pitts neural nets in 1969.
 2. In 1959–1960, a Cornell University professor, Frank Rosenblatt, had built a computer, the Perceptron, that implemented the McCulloch-Pitts neural net. Minsky and Papert asserted that such a machine could never solve more than the most primitive kind of logic problems.
 3. As a result, neural net development stopped until the mid-1980s.
- D.** Despite the flood of AI programs in the 1970s and early 1980s, however, top-down AI seemed to become stagnant.
1. The exponential increase in computer power from the mid-1970s masked the weakness of the mind-as-symbolic computer approach. Programming enough real-world knowledge into a computer to make functionally human-like reasoning possible began to seem overwhelming.
 2. Meanwhile, in the mid-1980s, Rosenblatt’s Perceptron was rehabilitated, the Minsky-Papert critique was rebutted, and the neural net approach to AI took on new life.

3. The neural net, or *bottom-up approach*, is fundamentally different conceptually from the top-down approach: Neural net programs are not algorithmic; knowledge and memory are stored in the connections between “neuron” nodes, not in symbolic form; information storage is distributed throughout the net; and nets display true learning by modifying the weights of their internal connections in order to achieve the desired output.

III. The combination of AI research, the cybernetics movement, the maturation of computer technologies, and the application of these technologies to the study of mind returns us to the question: What is the mind?

- A. In 1875, when Wundt began the study of experimental psychology, and through the period of Freud and Jung, no one would have doubted the reality of the mind.
- B. Behaviorism challenged the relevance of the mind but was replaced with cognitive psychology, in which mind does matter.
- C. Ironically, in cognitive science, we are now developing tools that increasingly suggest that what we call “the mind” is a network of physical and chemical activation patterns in the brain.
 1. We are beginning to identify localized functioning in the brain. For example, the prefrontal cortex seems to be the origin of decision making.
 2. Further, the brain can be electrically stimulated to duplicate experience. The DARPA-funded RoboRat and RoboMonkey showed that brain signals can be intercepted and used to control complex behaviors.
 3. There are approximately 10 billion neurons in the brain, and each of these has approximately 10,000 connections on average. Is what we call the mind “merely” activation patterns in an extremely complex network?

Essential Reading:

Howard Gardner, *The Mind’s New Science: A History of the Cognitive Revolution*.

Elkhonon Goldberg, *The Executive Brain: Frontal Lobes and the Civilized Mind*.

Steve Heims, *The Cybernetics Group*.

Supplementary Reading:

Rita Carter, *Mapping the Mind*.

Daniel Wegner, *The Illusion of Conscious Will*.

Questions to Consider:

1. Do machines display truly purposive behavior? Alternatively, what is there in human behavior that is more purposive than cybernetic machines display?
2. How is consciousness more than nervous system structure and programming, hard-wired and experiential?
3. Is artificial human-like conscious intelligence possible?

Lecture Thirty-Five

Looking Back

Scope: Looking back over the past 34 lectures, what are the central, new ideas of 20th-century science? Perhaps the most outstanding intellectual development cutting across the sciences has been the cluster of ideas associated with relational, systemic, and holistic thinking. The concepts of emergence and self-organization, the attention this has focused on nonequilibrium states, and the coordinate reassessment of control resulting from the development of neural networks are collateral ideas distinctive of late-20th-century science. The ideas associated with computer science and information theory; the emergence of self-consciousness in the practice of science and its implications for rethinking what we mean by knowledge, reality, truth, and objectivity; and recognition of the need for collaborative interdisciplinarity to do justice to natural phenomena in their full complexity are major intellectual innovations.

Outline

- I. In this lecture, I would like to share six provocative thoughts that can be abstracted from our survey of 20th-century science.
 - A. First, the scope, explanatory/predictive power, and applicability of science and scientific theories have progressively increased since the 17th century.
 1. This progress has not been linear. It was greater in the 19th century than in the 18th, and the rate of increase in scope and power accelerated throughout the 20th century, continuing into the 21st.
 2. Social factors have been major contributors to this acceleration, including the expansion of externally funded university-based scientific research and the career paths that opened in the sciences for large numbers of people. The sheer number of scientists working throughout the 20th century and into the 21st has contributed to the acceleration of scientific progress.
 3. The extraordinary increase in public and private funding of scientific research is another contributor to this rate of acceleration along with the increasing dependence of industry on science-based innovation for growth and competitiveness.
 4. Finally, a more subtle factor contributing to accelerated growth in scientific knowledge is the feedback into the research process of public and professional expectations: Science has been institutionalized such that scientists are expected to generate new knowledge and are rewarded for doing so.

- B. Second, though it is real progress, progress in scope and explanatory/descriptive power does *not* entail progress toward a definitively true account of (physical and social) reality.
 - 1. What we think there is “out there” when we use such terms as *atom, space, time, matter, universe, Earth, economy, and language* is, in fact, fundamentally different in 2000 from what we thought they meant in 1900.
 - 2. The inescapable lesson of history is that it is extremely unlikely that such changes have ended and that in 2100, we will still mean the same thing by these terms that we mean today.
 - 3. Further, it is not just science that has changed. Because science gives us an account of reality, we can say that *reality* has changed in the last 100 years.
- II. Third, let’s turn to seminal ideas within 20th century science that cut across disciplines and, thus, suggest a generic shift in intellectual approach.
 - A. It will come as no surprise that I call attention, first, to the idea of relationships.
 - 1. More accurately, I call attention to the cluster of ideas associated with the correlated concepts of network, structure, and relationship. These three ideas represent a new way of conceptualizing a wide range of realities.
 - 2. In the course of the 20th century, space, time, matter, energy, language, culture, society, history, and the economy have all been interpreted as continually changing networks of relationships with properties that are a function of the character of those relationships.
 - 3. Networks are relationship structures with properties that are a function of their structure, not of their nodes. This is as true of genes and proteins within the cell as it is of galactic clusters, as it is of the Internet!
 - B. Another seminal, cross-disciplinary idea is the concept of system.
 - 1. The system idea attributes a holistic character to phenomena. To understand a system you must understand how its parts are mutually adapted to function in that whole. This requires a top-down conceptualization of phenomena, not a bottom-up construction out of elements indifferent to their mutual adaptation.
 - 2. Holism, in turn, implies *emergence*, popularly: “the whole is greater than the sum of its part.” That is, systems have properties that do not exist at the level of the individual elements of the system. For example, neither sodium nor chlorine alone has anything like the properties of salt.
 - 3. Emergence has been understood only slowly and under considerable resistance, because the classical tradition held that the

world could be built up out of fundamental building blocks in a bottom-up process.

- C. Of course, we must also note the idea of dynamism that we have seen throughout this course—change is the norm.
 - 1. Natural and social systems are maintained in nonequilibrium states by energy inputs. Further, such systems often spontaneously organize themselves into complex structures.
 - 2. Nanotechnology research, for example, has revealed that under certain conditions, atoms and molecules will automatically organize themselves into carbon nanotubes or buckyballs.

III. Returning to our six provocative thoughts about 20th-century science, the fourth idea relates to complexity.

- A. Herbert Simon once defined a complex system as one whose behavior is unpredictable. For example, computer programs that are more than about 100,000 lines long exhibit fundamentally unpredictable behaviors (though quite short programs can, too). As we become increasingly interested in creating complex systems to take advantage of spontaneous self-organization, as in biotechnology, we are certain to see unpredictable results.
- B. Fifth, the relationship between scientific theorizing and instrument technologies intensified in the course of the century to an unprecedented degree. What we claim to know is increasingly a function of how we come to know it using knowledge-intensive artifacts.
 - 1. This process also works in reverse at times. Theories may stimulate the development of new technologies, as we saw with quantum theory and the invention of semiconductors, the transistor, and the laser.
 - 2. We should also note that social needs may have a relationship to technology, but rarely do they have a relationship to theories.
- C. Sixth, the 20th century has seen a shift away from “substance” explanations to a focus on processes and relationships.
 - 1. This suggests that we are maturing away from what John Dewey categorized as dichotomous thinking.
 - 2. Must we choose between top-down AI or bottom-up neural networks? Must we characterize phenomena as either matter or energy, either particle or wave? Such dichotomies can often be misleading in the attempt to describe reality.
- D. Finally, at the end of the 20th century and the beginning of the 21st, we should note the increasingly collaborative and cross-disciplinary nature of science, expressive of intellectual networking and the growing ability of science to deal with phenomena with minimal idealization.

Essential Reading:

Albert-Laszlo Barabasi, *Linked: How Everything Is Connected to Everything Else and What It Means for Business, Science, and Everyday Life*.

Mark C. Taylor, *The Moment of Complexity: Emerging Network Culture*.

Questions to Consider:

1. Science was obviously more powerful in 2000 than in 1900, but has it strengthened its position as the sole source of truth for society?
2. How can relational structures and information be the ultimate realities?
3. Can science retain its claim to “purity” given its 20th-century relationships to society, industry, and government?

Lecture Thirty-Six

Looking Around and Looking Ahead

Scope: Where are the sciences headed? What are the directions that are plotted for development over the next decade in the sciences and in technoscience, and what are the likely implications for science of globalization?

Outline

- I. In a dynamic, nonequilibrium environment, forecasting can be treacherous and prediction downright foolhardy, but we may be able to see some directions that science will take in the 21st century.
 - A. One branch of science that seems likely to change is astrophysics, with the “discovery” of *dark energy*.
 1. As we discussed in past lectures, some force seems to be at work in accelerating the expansion of the universe.
 2. This force seems to have manifested itself when the universe was about 7 billion years old. Before that, it may have been masked by gravity.
 3. Since 1998, there has been a steady accumulation of evidence supporting the reality of this acceleration.
 4. Recall that, in 1900, Lord Kelvin announced that science seemed to be approaching a definitive account of nature. Two “small clouds” remained: the inability to explain the blackbody radiation problem and the inability to measure the speed of the Earth relative to absolute space. Resolving these problems led to quantum mechanics and relativity theory, which totally transformed physics as it was in 1900.
 5. Dark energy may be a similar “small cloud” that will require a fundamental change in gravitational theory.
 - B. Recent observations tell astronomers that galactic clusters existed when the universe was less than 3 billion years old, at a time when, according to inflation theory, the universe could not have had that much structure. This is another question facing astrophysics.
 - C. Still another challenge relates to whether we are reading the microwave background radiation correctly, which is the basis for much of our current understanding of the structure of the universe.
 - D. The Standard Model in physics, that is, the unification of electro-weak theory and QCD, continues to be plagued in the 21th century by a poor fit with having to assign mass to neutrinos. Also hovering over the Standard Model is the specter of the Higgs boson, which should be detected when CERN goes back online in a few years. Finding it will

strongly reinforce the radical conception that mass is an energy phenomenon.

- E. Confirming gravity waves will reinforce pursuit of a quantum theory of gravity. Even more dramatic, however, would be a breakthrough in the information structure theory of the universe.

II. Twenty-first-century science will also see increasing involvement in biotechnology.

- A. It is fairly obvious that we are only beginning to understand genetics and the wider processes of intra- and inter-cellular signaling, as well as regulatory and monitoring networks that affect cellular metabolism. The action of genes is actually far more complex than we believed to be the case in the 1960s.
- B. It seems inevitable that medicine in 2000 will be judged in 2100 to be as pitifully powerless as medicine in 1900 was judged to be in 2000. Think a bit about the implications of that.

III. The direction of social science research is harder to foresee.

- A. One of the most puzzling findings of anthropology and archaeology is the acceleration of cultural development among *Homo sapiens* starting approximately 12,000 years ago, which included organized settlements, long-distance trade, communal production, structures of authority, and social order. Perhaps the 21st century will shed some light on our own cultural evolution in this regard.
- B. The assault on consciousness via brain-mind correlation studies, molecular neuroscience, and various approaches to AI is sure to accelerate. We do not yet grasp the implications of *naturalizing* consciousness. When consciousness is reduced to a structural phenomenon that we can model in a machine, what will be left for our self-image?
 - 1. In the course of 300-year history of modern science, our biological existence has been naturalized. Our bodies have been reduced to physical and chemical processes, but throughout the 19th century, when this naturalization was taking place, the assumption was that our consciousness set us apart from other organisms.
 - 2. Freud represented an early foray into the elimination of that privileged characteristic by emphasizing the unconscious. Since Freud, scientists have attempted to gain an understanding of consciousness, primarily by reducing it to a physical phenomenon.
 - 3. What happens if we discover that *mind* is nothing more than an emergent property of a particular kind of network structure?

IV. We are already committed to creating technological innovations based on self-organized, complex systems, which by definition, have unpredictable characteristics. We should be forewarned that these new technologies will

surprise us because complex systems are unpredictable, and these surprises will not all be pleasant!

- V. The science-technology-society relationship now seems irreversible.
 - A. Science has definitively lost its innocence. It can no longer claim to generate value-neutral, objective knowledge. The pursuit of scientific knowledge is firmly embedded in social institutions and expectations.
 - B. Science has been the recipient of public funding and support, because the public perceives that science is a source of technological benefit. If, however, we experience calamities in the 21st century that can be traced to technologies enabled by science, as many believe we will, science will suffer a backlash.
 - C. We have seen that physical scientists are moving toward the goal of unifying the four fundamental forces of nature: the strong force, the weak force, the gravitational force, and the electromagnetic force.
 - 1. However, science in the 21st century may itself be caught up in a growing cultural unification.
 - 2. Scientific theories are beginning to unify philosophy, metaphysics, theology, and science. They are reaching such a degree of complexity, sophistication, and intellectual power that they touch on questions that were previously reserved for religion and philosophy.
 - D. The Olympics are a mosaic of the physical capabilities of human beings. In the same way, the sciences are a mosaic of our cognitive response to experience.
 - 1. But science is not merely a cognitive response to experience. Our survey of the history of science in the 20th century should have given us some insight into an interesting methodological practice of scientists: *bricolage*.
 - 2. *Bricolage* involves creating a work of art out of materials found lying about, selectively incorporating these ordinary materials into a work of art.
 - 3. What we have seen of the evolution of the physical and life sciences is just such a selective, opportunistic employment of ideas and techniques “lying about” as a result of apparently unrelated work by others.
 - 4. It is suggestive, then, that behind its formidable technicality, science is as aesthetic as it is intellectual, and I hope that this survey has helped to illuminate some of the intellectual riches of 20th-century scientific theory.

Essential Reading:

John Brockman, *The Next Fifty Years: Science in the First Half of the 21st Century*.

Philip Kitcher, *Science, Truth and Democracy*.

Martin Rees, *Our Final Hour: A Scientist's Warning: How Terror, Error, and Environmental Disaster Threaten Humankind's Future in This Century—On Earth and Beyond*.

Supplementary Reading:

Gunther Stent, *The Coming of the Golden Age: An End to Progress*.

Questions to Consider:

1. If planned experiments and current research lead to a successful quantum theory of gravity and the unification of the four fundamental forces of physical science, is science over, except for details and applications?
2. Is a global science emerging or a globalization of Western science, and what difference would that make?
3. Are biotechnology, nanotechnology, and AI/robotics laying the groundwork for 21st-century calamities more damaging than we will be able to control?

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Close, Frank, Michael Marten, and Christine Sutton. *The Particle Odyssey: A Journey to the Heart of the Matter*. Oxford: Oxford University Press, 2002. This looks like a coffee-table book and can be one, but it is an excellent history of particle accelerators. Highly recommended.

Cohen, Jack, and Ian Stewart. *The Collapse of Chaos: Discovering Simplicity in a Complex World*. London: Penguin, 1995. A very good popular account of chaos theory, its implications, and applications.

Coleman, William. *Biology in the Nineteenth Century: Problems of Form, Function, and Transformation*. New York: John Wiley and Sons, 1971. Out of print but an excellent account of the major ideas in 19th-century biology.

Collins, Randall. *Four Sociological Traditions: Selected Readings*. Oxford: Oxford University Press, 1994. A very good account of major sociological theories.

Cook, Michael. *A Brief History of the Human Race*. New York: Norton, 2003. In addition to an overview of human evolution from hominid to *Homo sapiens*, this book addresses the puzzling question of the rapidity of cultural evolution over the past 12,000 years.

Cutcliffe, Stephen. *Ideas, Machines and Values: An Introduction to Science, Technology, and Society Studies*. Lanham, MD: Rowman, Littlefield, 2002. A short, clear presentation of the mutual relationship of science, technology, and society by one of the leading figures in the field.

Damasio, Antonio. *Descartes' Error: Emotion, Reason, and the Human Brain*. New York: Avon, 1995. A highly intelligent popular treatment of the dominance of rationalism in modern Western intellectualism. Recommended.

———. *The Feeling of What Happens: Body and Emotion in the Making of Consciousness*. Orlando: Harcourt, 2000. A popular but rich and accurate account of the neural basis of consciousness.

Degler, Carl. *In Search of Human Nature: The Decline and Revival of Darwinism in American Social Thought*. Oxford: Oxford University Press, 1992. Prize-winning history of theories of human nature from the late 19th through the late 20th centuries. Very well written and full of insights into how scientists reach conclusions. Highly recommended, especially with Lewin's *Bones of Contention*.

Dennett, Daniel C. *Darwin's Dangerous Idea: Evolution and the Meanings of Life*. New York: Simon and Shuster, 1996. A philosopher of mind develops the implications of Darwinism for our self-image and our values. Provocative and controversial.

Devlin, Keith. *Mathematics: The New Golden Age*. New York: Columbia University Press, 1999. A very readable discussion of the ideas underlying contemporary mathematics and their broader scientific and technological significance.

Dryzek, John, James Farr, and Stephen T. Leonard. *Political Science in History: Research Programs and Political Traditions*. Cambridge: Cambridge University Press, 1995. A fine collection of essays reflecting the 20th-century history of political science as a discipline.

Einstein, Albert. *Relativity: The Special and General Theories*. New York: Three Rivers Press, 1995. A popular account, so why not read about it from the man himself?

Fancher, Raymond E. *The Intelligence Men: Makers of the IQ Controversy*. New York: Norton, 1987. An excellent history of intelligence tests and their social consequences. Recommended.

Ferris, Timothy. *The Whole Shebang: A State-of-the-Universe(s) Report*. New York: Simon and Shuster, 1998. First-rate science writing by a veteran, here describing for a general audience what physicists knew about the universe by 1997.

Feynman, Richard. *Surely You're Joking, Mr. Feynman: Adventures of a Curious Character*. New York: Norton, 1997. Feynman was one of the creators of mature quantum electrodynamics and a true character, as these irreverent autobiographical anecdotes reveal.

Freud, Sigmund. *The Ego and the Id*. New York: Norton, 1976. An excellent short introduction to central ideas of Freudian psychoanalysis.

Galambos, Louis, and J. E. Sewell. *Networks of Innovation: Vaccine Development at Merck, Sharp and Dohme, and Mulford, 1895–1995*. Cambridge: Cambridge University Press, 1995. A valuable analysis with case studies of the innovation process.

Gamow, George. *Thirty Years That Shook Physics: The Story of Quantum Theory*. New York: Dover, 1985. A colorful, concise memoir, by one who was there, of the origins of quantum mechanics. Full of lively anecdotes and personal observations. Highly recommended.

Gardner, Howard. *The Mind's New Science: A History of the Cognitive Revolution*. New York: Basic Books, 1987. A very readable history of the rise and early years of cognitive psychology.

Gazzaniga, Michael S. *The Mind's Past*. Berkeley: University of California Press, 2000. Gazzaniga is an eminent neurosurgeon and neuroscientist who has

written an informal account of our current understanding of the mind-brain relationship.

Geertz, Clifford. *The Interpretation of Cultures*. New York: Basic Books, 2000. A stimulating collection of lively essays by the leading proponent of interpreting cultures as symbol systems. Recommended.

Gell-Mann, Murray. *The Quark and the Jaguar: Adventures in the Simple and the Complex*. New York: Henry Holt, 1995. From the man who created the Eightfold Way and quantum chromodynamics with all their witty names, this autobiographical memoir is surprisingly heavy going, but if your library has a copy, try it.

Goldberg, Elkhonon. *The Executive Brain: Frontal Lobes and the Civilized Mind*. Oxford: Oxford University Press, 2002. Goldberg presents a nontechnical argument for the localization of conscious decision-making in a network centered in the forebrain.

Goldman, Steven L. *Science, Technology, and Human Progress*. Bethlehem: Lehigh University Press, 1989. A collection of thought-provoking essays by scientists, historians, philosophers, and sociologists on the reality of science and technology-driven social progress.

Gossett, Thomas F. *Race: The History of an Idea in America*. Oxford: Oxford University Press, 1997. The title says it all. Very fine and disturbing social history.

Gould, Stephen Jay. *Wonderful Life: The Burgess Shale and the Nature of History*. New York: Norton, 1992. A passionate and controversial account, based on 500-million-year-old fossils, of the fundamental contingency of evolution by an eminent paleontologist who writes exceptionally well. The opposing view is found in Morris, below.

Greene, Brian. *The Elegant Universe: Superstrings, Hidden Dimensions, and the Quest for the Ultimate Theory*. New York: Knopf, 2000. An elegant account of the state of our knowledge of the cosmos at the turn of the 20th century. Highly recommended.

———. *The Fabric of the Cosmos: Space, Time, and the Texture of Reality*. New York: Knopf 2004. An updated and extended version of the author's earlier book, putting string theory in historical context from Newton through Einstein to the theory of everything.

Gribbin, John. *In Search of Schrödinger's Cat: Quantum Physics and Reality*. New York: Bantam, 1984. A clear discussion by a physicist of the issue that separated Einstein and Bohr, namely, the finality of quantum mechanics, as epitomized in a startling thought experiment.

———. *Schrödinger's Kittens and the Search for Reality*. New York: Little, Brown, 1996. This supplements Gribbin's earlier book, focusing on important developments in the intervening years.

Guth, Alan. *The Inflationary Universe: The Quest for a New Theory of Cosmic Origins*. New York: Perseus, 1998. Learn about cosmic inflation from its inventor.

Hacking, Ian. *The Social Construction of What?* Cambridge, MA: Harvard University Press, 2000. A first-rate discussion of the Science Wars by a first-rate philosopher of science. Highly recommended.

Harman, P. M. *Energy, Force and Matter: The Conceptual Development of Nineteenth-Century Physics*. Cambridge: Cambridge University Press, 1982. Out of print but easy to find and well worth it as an excellent overview of 19th-century physics and chemistry.

Harris, Roy. *Language, Saussure and Wittgenstein: How to Play Games with Words*. London: Routledge, 1990. An excellent introduction to the philosophical implications of language in de Saussure and in Ludwig Wittgenstein, arguably one of the three most influential philosophers of the century.

———. *The Language Machine*. London: Duckworth, 1987. Harris writes extremely well, here about language itself.

Hawking, Stephen. *A Brief History of Time*. New York: Bantam, 1998. Truly a brief account of space, time, gravity, and black holes by the dean of black hole theorists.

Heims, Steve J. *The Cybernetics Group*. Cambridge, MA: MIT Press, 1991. A rich account of the evolution of cybernetics, information theory, and artificial intelligence research out of the 1942–1952 Macy Foundation conferences. (Also titled: *Constructing a Social Science for Post-War America*.)

Hodge, Andrew. *Alan Turing: The Enigma*. New York: Walker, 2000. A reissue of an excellent 1983 biography of Turing and his creation of the concept of the modern computer.

Holland, John. *Emergence: From Chaos to Order*. New York: Perseus, 1999. Holland is one of the founders of complexity theory and self-organizing systems, and this is a very readable introduction to these ideas.

Holmes, Frederic L. *Meselson, Stahl and the Replication of DNA: A History of "The Most Beautiful Experiment in Biology."* New Haven: Yale University Press, 2002. A long but fascinating and definitive history of the "most beautiful experiment in biology," one that proved how DNA replicated.

Hughes, Thomas. *American Genesis: A History of the American Genius for Invention*. London: Penguin, 1990. A fine history of technological innovation in America from its foundation to the late 20th century.

———. *Networks of Power: Electrification in Western Society, 1880–1930*. Baltimore: Johns Hopkins University Press, 1993. An outstanding exploration of the social dimension of technological innovation. Highly recommended.

Johnson, Mathew. *Archaeological Theory: An Introduction*. Oxford: Blackwell, 1999. A fine, serious survey of the spectrum of archaeological theories in the 19th and 20th centuries.

Jung, Carl. *Archetypes and the Collective Unconscious*, vol. 9 of the *Collected Works*. Princeton University Press, 1976. In Jung's own words, the core ideas of his theory.

Kevles, Bettyann. *Naked to the Bone: Medical Imaging in the Twentieth Century*. New York: Perseus, 1998. First-rate history of all the medical imaging technologies, from X-rays to PET scans.

Kevles, Daniel. *In the Name of Eugenics: Genetics and the Uses of Human Heredity*. Cambridge, MA: Harvard University Press, 1995. An excellent social history of the eugenics controversy and compulsory sterilization laws in the first half of the 20th century.

———. *The Physicists: The History of a Scientific Community in Modern America*. Cambridge, MA: Harvard University Press, 1995. Practically the “gold standard” for social history of science, in this case, the evolution of the U.S. physics community and its relationship to society from the mid-19th century to the present.

Kitcher, Philip. *Science, Truth and Democracy*. Oxford: Oxford University Press, 2001. An extremely thoughtful discussion of the social relations and implications of scientific knowledge. Highly recommended.

Kragh, Helga. *Cosmology and Controversy*. Princeton: Princeton University Press, 1999. Contrasts the Big Bang and Steady State theories of the universe. Excellent professional history of physics and highly recommended.

———. *Quantum Generations: A History of Physics in the Twentieth Century*. Princeton: Princeton University Press, 2002. A first-rate professional history of 20th-century physics, not just quantum theory. Highly recommended.

Kuhn, Thomas. *The Structure of Scientific Revolutions*. Chicago: University of Chicago Press, 1996. This is the book that launched the 1960s critique of objectivity, arguing that theory change was, in part, a social phenomenon.

Lakoff, George, and Mark Johnson. *Philosophy in the Flesh: The Embodied Mind and its Challenge to Western Thought*. New York: Basic Books, 1999. Philosophy and linguistics enriched by cognitive science. Recommended.

Levere, Trevor. *Transforming Matter: A History of Chemistry from Alchemy to the Buckyball*. Baltimore: Johns Hopkins University Press, 2001. A concise, readable history of chemistry.

Lewin, Roger. *Bones of Contention: Controversies in the Search for Human Origins*. Chicago: University of Chicago Press, 1997. Prize-winning history of the personal struggles and controversies underlying the interpretation of human fossils. Highly recommended.

Mandelbrot, Benoit. *The Fractal Geometry of Nature*. New York: Henry Holt, 1984. From the hands of the man who did it, the description of the creation of a fascinating and beautiful new branch of mathematics with growing applications.

Mann, Alfred K. *For Better or For Worse: The Marriage of Science and Government in the U.S.* New York: Columbia University Press, 2000. A short,

well-written, and highly informative history of federal support for physical and life science from the creation in 1940 of the Office of Scientific Research and Development to the cancellation of the Superconducting Super Collider in 1994, and a little after.

Mayr, Ernst. *The Growth of Biological Thought: Diversity, Evolution, and Inheritance*. Cambridge, MA: Harvard University Press, 1985. A massive and masterly intellectual history of biology by a master biologist.

———. *What Evolution Is*. New York: Basic Books, 2002. A compact, passionate, but thoughtful turn-of-the-21st-century argument for evolution by one of the architects of neo-Darwinism.

Mazower, Mark. *Dark Continent: Europe's Twentieth Century*. New York: Random House, 2000. An excellent, insightful, and deeply disturbing political history of Europe, especially good for the interwar decades. Highly recommended.

McDougall, Walter A. *The Heavens and the Earth: A Political History of the Space Age*. Baltimore: Johns Hopkins University Press, 1997. An updated edition of a classic history of the American space program.

McNeill, J. R. *Something New under the Sun: An Environmental History of the Twentieth-Century World*. New York: Norton, 2001. A very good complement to Bowler's book, above.

McPhee, John. *Annals of the Former World*. New York: Farrar, Straus and Giroux, 1999. McPhee is the most literary science writer of our time, and his essays on geology, primarily the majestic basin-and-range geology of the American west, are gems. Highly recommended.

Mills, C. Wright. *The Power Elite*. Oxford: Oxford University Press, 1999. Reissue of a classic 1950s political scientific analysis of the covert power centers in American public life.

Morange, M. *A History of Molecular Biology*. Cambridge, MA: Harvard University Press, 2000. What it says, and very good; plus it's by a "player."

———. *The Misunderstood Gene*. Cambridge, MA: Harvard University Press, 2002. An important argument against the popular hype about DNA and genetic engineering, that corrects widespread misperception of what genes are and do.

Morris, Simon Conway. *Life's Solution: Inevitable Humans in a Lonely Universe*. Cambridge: Cambridge University Press, 2003. Morris's rejoinder to Gould's claim in *Wonderful Life* that evolution is unpredictable. Morris argues lucidly and provocatively for an opposing view.

———. *The Crucible of Creation: The Burgess Shale and the Rise of Animals*. Oxford: Oxford University Press, 1998. Not in print but worth finding. Morris was one of the scientists whose research was the basis for Gould's *Wonderful Life*. Here, Morris presents his own interpretation of fossils at the dawn of animal evolution.

Nagel, E., and J. R. Newman. *Gödel's Proof*. New York: New York University Press, 2001. A wonderfully intelligible presentation of Gödel's proof that the completeness and consistency of mathematics cannot be proven. Much more than worth the effort, for which only high school level math is required.

Newmeyer, F. J. *Linguistic Theory in America*. London: Elsevier, 1986. For those with a background in linguistics, very good.

Novick, Peter. *That Noble Dream: The "Objectivity Question" and the American Historical Profession*. Cambridge: Cambridge University Press, 1988. An exceptionally intelligent history of changing attitudes toward history in the United States in the 20th century.

Nye, Mary Jo. *Before Big Science: The Pursuit of Modern Chemistry and Physics, 1800–1940*. Cambridge, MA: Harvard University Press, 1999. An excellent, short, lively account of chemistry and physics in the 19th and first half of the 20th centuries. Highly recommended.

Oreskes, Naomi. *Plate Tectonics: An Insider's History of the Modern Theory of the Earth*. Cambridge, MA: Perseus, 2003. A very readable collection of informal essays by many of the leading contributors on their parts in creating plate tectonic theory.

———. *The Rejection of Continental Drift: Theory and Method in American Earth Science*. Oxford: Oxford University Press, 1999. An outstanding history of the resistance of American geologists to the idea of moving continents and how this resistance was overcome. Highly recommended.

Overbye, Dennis. *Lonely Hearts of the Cosmos: The Story of the Scientific Quest for the Secret of the Universe*. New York: Little, Brown, 1999. Science writing at its best. Overbye presents the human side of the development of cosmology in the 20th century without sacrificing the science.

Pais, Abraham. *The Genius of Science: A portrait gallery of twentieth-century physicists*. Oxford: Oxford University Press. Pais was a participant in the postwar evolution of quantum electrodynamics who has written a series of readable books about physics that are rich in content.

———. *Subtle Is the Lord: The Science and the Life of Albert Einstein*. Oxford: Oxford University Press, 1983. No longer in print but worth looking for as a discussion of the issues that separated Einstein and Bohr over the meaning of quantum mechanics.

———. *Einstein Lived Here: Essays for the Layman*. Oxford: Oxford University Press, 1994. A biography of Einstein that focuses on his ideas and their impact. Not in print but available used and in libraries.

———. *Niels Bohr's Times: In Physics, Philosophy, and Polity*. Oxford: Oxford University Press, 1991. Out of print but not hard to find and an excellent intellectual biography, not only of Bohr but of all those who created quantum mechanics.

Pickering, Andrew. *Constructing Quarks: A Sociological History of Particle Physics*. Chicago: University of Chicago Press, 1986. One of the best examples of post-Kuhn philosophy of science, teasing out the social dimension of the creation of scientific theories.

Pinker, Steven. *How the Mind Works*. New York: Norton, 1998. Cognitive neuroscience for the general public by an insider. A very big book.

Provine, William. *The Origins of Theoretical Population Genetics*. Chicago: University of Chicago Press, 2001. Happily reissued, this is an excellent history of the revival of Darwinism in the 1920s and 1930s through its unification with population-based genetics. Highly recommended.

Rabinow, Paul. *Making PCR: A Story of Biotechnology*. Chicago: University of Chicago Press, 1997. A concise, fascinating history of the invention of the DNA-segment-replicating technique that accelerated progress in molecular biology and the creation of a biotechnology industry.

Rees, Martin. *Just Six Numbers: The Deep Forces That Shape the Universe*. New York: Basic Books, 2001. Bestselling popular account by England's Astronomer Royal of the significance for our understanding of reality of six constants that crop up in the laws of physics. Highly recommended.

———. *Our Final Hour: A Scientist's Warning: How Terror, Error, and Environmental Disaster Threaten Humankind's Future in This Century—On Earth and Beyond*. New York: Basic Books, 2003. An extraordinarily pessimistic projection of the likely collapse of civilization as we know it by 2100 by an eminent scientist.

Renaut, Alain. *The Era of the Individual: A Contribution to a History of Subjectivity*. Princeton: Princeton University Press, 1999. Not an easy read stylistically but a passionate and insightful critique of post-modernism and a defense of "constructive" individualism.

Robinson, Daniel N. *An Intellectual History of Psychology*. Madison: University of Wisconsin Press, 1995. Part 3 provides valuable background to Lecture Thirty-Three.

Rose, Hilary, and Steven Rose. *Alas, Poor Darwin: Arguments against Evolutionary Psychology*. New York: Crown, 2000. A stimulating collection of essays critical of evolutionary psychology.

Ross, Dorothy. *The Origins of American Social Science*. Cambridge: Cambridge University Press, 1992. A classic historical study.

Sahlins, Marshall. *Culture and Practical Reason*. Chicago: University of Chicago Press, 1978. With Geertz, above, Sahlins defected from a materialistic interpretation of culture to a humanistic-symbolic one. These essays reveal why.

Sampson, Geoffrey. *Schools of Linguistics*. Stanford: Stanford University Press, 1990. An excellent, very readable survey of 20th-century linguistics. Highly recommended.

Saussure, Ferdinand de. *Course in General Linguistics*. New York: Open Court, 1990. This is the text created by de Saussure's students from lecture notes that presented his language theory to the world. If you're interested in linguistics, read it!

Schweber, Silvan. *QED and the Men Who Made It: Dyson, Feynman, Schwinger, and Tomonaga*. Princeton: Princeton University Press, 1994. The definitive history of quantum electrodynamics, but some background in physics is required to appreciate it.

Shapiro, Stewart. *Thinking about Mathematics: The Philosophy of Mathematics*. Oxford: Oxford University Press, 2000. I know of no better nontechnical account of the philosophical issues posed by mathematics, as discussed in Lectures Nine and Ten.

Shipman, P., and E. Trinkaus. *The Neandertals: Changing the Image of Mankind*. New York: Knopf, 1992. An excellent history of the controversies over the interpretation of fossil human remains.

Sismondo, Sergio. *An Introduction to Science and Technology Studies*. Oxford: Blackwell, 2004. Up-to-date introduction to the science-technology-society relationship.

Skidelsky, Robert. *John Maynard Keynes: Fighting for Freedom, 1937–1946*. London: Penguin, 1993–2002. An excellent three-volume intellectual and social biography of Keynes, surely one of the few 20th-century intellectuals worthy of such treatment. Recommended.

Skinner, B. F. *Beyond Freedom and Dignity*. New York: Knopf, 1971. This highly controversial book turned out to be the high watermark of Skinnerian behaviorism.

Smolin, Lee. *The Life of the Cosmos*. Oxford: Oxford University Press, 1998. An excellent nontechnical monograph on the evolution of the universe and, thus, of the laws of physics themselves. Recommended.

———. *Three Roads to Quantum Gravity*. New York: Basic Books, 2003. The best compact and nontechnical discussion of the final unification theory. Highly recommended.

Stachel, John. *Einstein's Miraculous Year*. Princeton: Princeton University Press, 1998. An excellent description of the epochal papers Einstein published in 1905, written by a noted physicist who edited the "official" collection of Einstein's writings.

Stent, Gunther. *The Coming of the Golden Age: An End to Progress*. New York: Doubleday, 1969. Still to be found and a very provocative essay by a molecular biologist on the prospect of an end to new scientific theories and even of new cultural forms. And what then?

Stones, Rob. *Key Sociological Thinkers*. New York: New York University Press, 1998. A good survey of sociological theories from Marx to the late 20th century.

Taylor, Mark C. *The Moment of Complexity: Emerging Network Culture*. Chicago: University of Chicago Press, 2003. Embedded in this rather flamboyantly literary account are some of the most provocative ideas of our time relating to self-organizing systems, networks, information, systems theory, emergence, and complexity. Recommended, but hang in there!

Treiman, Sam. *The Odd Quantum*. Princeton: Princeton University Press, 1999. A physicist offers a lively popular account of the implications of quantum physics for what we mean by “reality.”

Trigger, Bruce. *A History of Archaeological Thought*. Cambridge: Cambridge University Press, 1990. An excellent history of the evolution of archaeological thought. Highly recommended.

Tucker, Wallace, and Karen Tucker. *The Cosmic Inquirers*. Lincoln, NE: iUniverse, 1999. A popular but very good history of post-World War II telescoping, especially radiotelescopes and satellite observatories. Recommended.

Watson, James D. *DNA: The Secret of Life*. New York: Knopf, 2003. Wonderful, easy-to-read, informal text on biology after DNA, by the co-discoverer of the structure of DNA.

———. *The Double Helix: A Personal Account of the Discovery of the Structure of DNA*. New York: Simon and Shuster, 2001. The latest reissue of Watson’s near-scandalous account of how he and Crick discovered the structure of DNA. Not to be missed.

Wegner, Daniel. *The Illusion of Conscious Will*. Cambridge, MA: MIT Press, 2003. A provocative argument based on growing experimental evidence that conscious will is an illusion. Recommended.

Wilson, Edward O. *On Human Nature*. Cambridge, MA: Harvard University Press, 1988. A leading evolutionary biologist and founder of sociobiology writes for a general audience on what he thinks the implications of evolution are for human beings in the world. Highly provocative.

———. *Sociobiology: The New Synthesis*. Cambridge, MA: Harvard University Press, 2000. This is an updated version of the book that started it all, arguing that all human behavior and values are biological in origin.

Yandell, Benjamin H. *The Honors Class: Hilbert’s Problems and Their Solvers*. Natick, MA: A K Peters, 2002. A clear account for non-mathematicians of Hilbert’s challenge problems and the mathematicians who solved them. Highly recommended.

Web Sites and Magazines:

An excellent resource for the history of space exploration is the web site maintained by NASA: www.spaceflight.nasa.gov/history.

On comparative planetology, see the web site maintained (in English) by the Institute for Planetology at the University of Muenster in Germany:
<http://ifp.uni-muenster.de/links/worldlnk.phtml>.

By far the best reference source for the history of economics is the web site *History of Economic Thought* maintained by the New School for Social Research in New York City: www.cepa.newschool.edu/het/

American Scientist, the magazine of Sigma Xi, the Scientific Research Society, is an outstanding source of excellent, professionally prepared articles for non-specialist readers on all aspects of science.